Landscape Assessment (LA)

Sampling and Analysis Methods

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SUMMARY

Landscape Assessment primarily addresses the need to identify and quantify fire effects over large areas, at times involving many burns. In contrast to individual case studies, the ability to compare results is emphasized along with the capacity to aggregate information across broad regions and over time. Results show the spatial heterogeneity of burns and how fire interacts with vegetation and topography. The quantity measured and mapped is "burn severity," defined here as a scaled index gauging the magnitude of ecological change caused by fire. In the process, two methodologies are integrated. Burn Remote Sensing (BR) involves remote sensing with Landsat 30-meter data and a derived radiometric value called the Normalized Burn Ratio (NBR). The NBR is temporally differenced between pre- and postfire datasets to determine the extent and degree of change detected from burning (fig. LA-1). Two timeframes of acquisition identify effects soon after fire and during the next growing season for Initial and Extended Assessments, respectively. The latter includes vegetative recovery potential and delayed mortality. The Burn Index (BI) adds a complementary field sampling approach, called the Composite Burn Index (CBI). It entails a relatively large plot, independent severity ratings for individual strata, and a synoptic rating for the whole plot area. Plot sampling may be used to

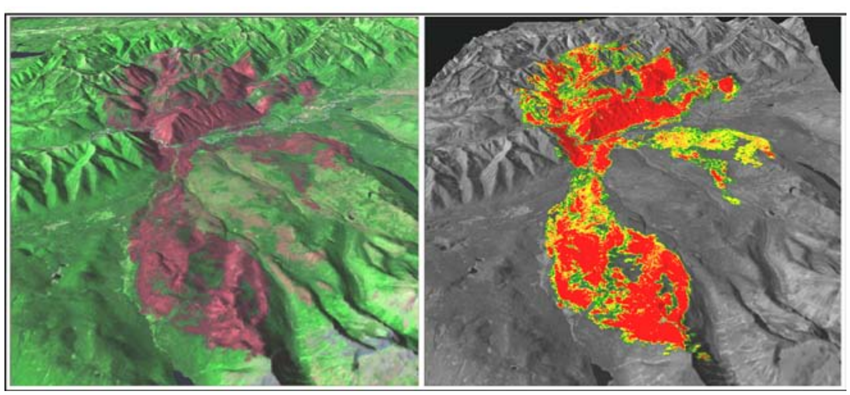

Figure LA-1—A three-D view of the Moose fire, northwestern Montana, taken by Landsat ETM+ on 9 September 2001. On the left, spectral Band 4 and Band 7 are displayed as a composite of green and red, respectively. On the right, differencing the NBR before and after fire has derived an initial assessment of burn severity. The gradient of differenced NBR has been stratified to identify burn severity levels, including: unburned, low (green), moderate-low (yellow), moderate-high (orange), and high (red).

calibrate and validate remote sensing results, to relate detected radiometric change to actual fire effects on the ground. Alternatively, plot sampling may be implemented in stand-alone field surveys for individual site assessment.

INTRODUCTION

Methods in this chapter are designed to provide a landscape perspective on fire effects. That is, spatial data on burn severity throughout a whole burn. They show the results of fire in context of regional biophysical characteristics, such as topography, climate, vegetation, hydrography, fuels, and soil. At this level, one can isolate burned from unburned surroundings, measure the amount burned at various levels of effect, and gauge the spatial heterogeneity of the burn (fig. LA-2). Such methods provide a quantitative picture of the whole burn as if viewed from the air. They are adapted to remote sensing and GIS technologies, which in turn produce a variety of derived products such as maps, images, and statistical summaries.

The authors first developed the methods in 1996, following analysis of wildfires that occurred in Glacier National Park during 1994. Since that time, efforts were made to bring the remote sensing and field approaches of dNBR and CBI into an operational setting for national burn area mapping. As a component of that, the first version of documentation appeared in FIREMON in 2001, and was made available on the FIREMON Web site. Subsequently, minor revisions were made in 2002 and 2003. Documentation has been updated in Version 4 to reflect experience gained over recent field seasons. Changes were made to clarify some issues with the timing of Landsat data acquisitions and how that relates to burn severity, and also to refine severity rating-factor definitions to make ground sampling more broadly applicable across ecosystems of the United States. To implement landscape assessment of burns, several factors must be considered; among them scale, resolution, standardization, and cost effectiveness. Methods herein furnish information covering potentially several tens of thousands of square kilometers at a time, with capability to monitor large or inaccessible burns (fig. LA-3). Small burns of a few hectares can be monitored as well, but that may not be cost effective unless those are

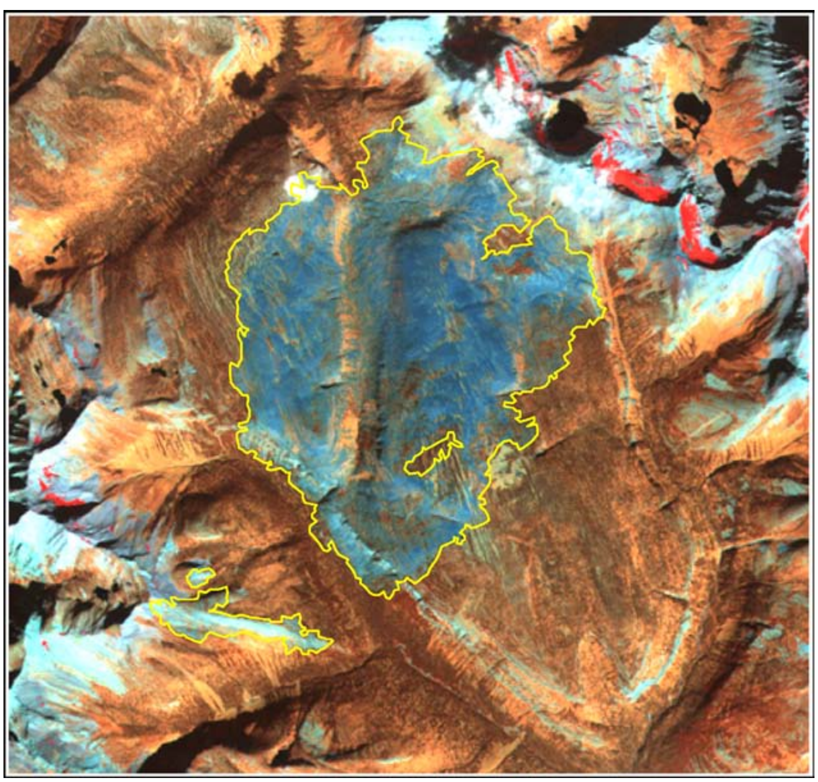

Figure LA-2—The Kootenai Complex from the interior of Glacier National Park captured by Landsat 12 September 1999, a year after the fire. The range of colors within the perimeter shows patterns of burning, gradations of reddish-brown (no burn to low severity) through dark blue (high severity). Information about how the fire interacted with the landscape is also evident. Red areas are perennial snowfields and glaciers nestled among the rocky peaks (light blue to white).

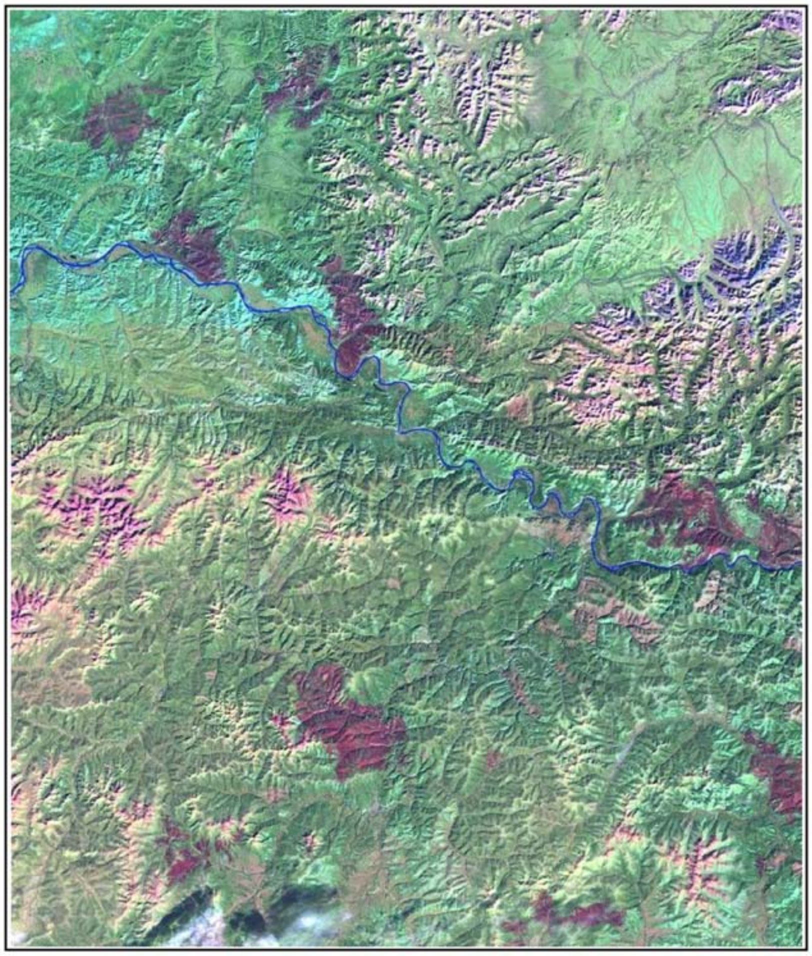

Figure LA-3—This mosaic of two Landsat 7 ETM+ scenes from 12 Sept 1999, shows the Yukon Charlie region of Alaska. Nine large burns are clearly visible (dark purple) from fires earlier in the summer. This type of remote sensing data allows managers to discover details of burns, which because of daunting logistics, may never be visited on the ground. The challenge has been to find the best measure of severity from such data, and to develop protocols that offer standardization, so burns can be compared spatially and temporally.

covered in conjunction with other large burns. Cost per unit area diminishes as burn area increases over a region. Products also are useful to the manager dealing with local burn issues. Important to note is that objectives are for standard approaches that can be applied uniformly over multiple concurrent burns and that yield comparable metrics from region to region over time. This section identifies data sources and methods that can be broadly implemented on a national level for repeatable and routine assessment at an affordable cost—that is, in terms of the Federal and State land-based agencies accountable for wildland burn programs.

The Landsat satellite program has been well suited for burn area assessment. Landsat archives contain near global repeat coverage of multispectral data acquired since 1982 at 30-meter spatial resolution. With two operational satellites as of 2003 (Landsat 5 and Landsat 7), data acquisition is possible every 8 days. Unfortunately in spring of 2003, Landsat 7 developed the now well-known scan line corrector problem, which results in missing lines of data through portions of each scene. This data can still be used in some burn assessments, however, where missing data does not impact the burned area, or where multiple scenes can be patched together to fill the missing lines. Most important, Landsat is the only source for temporally and spatially consistent information on a continual basis nationwide. It allows one to compare both prefire and postfire conditions when evaluating the magnitude of fire-caused change (fig. LA-4). Moreover, resolution is efficient for broad-area coverage, in terms of computer resources and funds available to most land managers today. Such characteristics are key to methodologies presented here for whole-burn monitoring. For more information, contact the USGS Landsat 7 Web site at: http://landsat7.usgs.gov/.

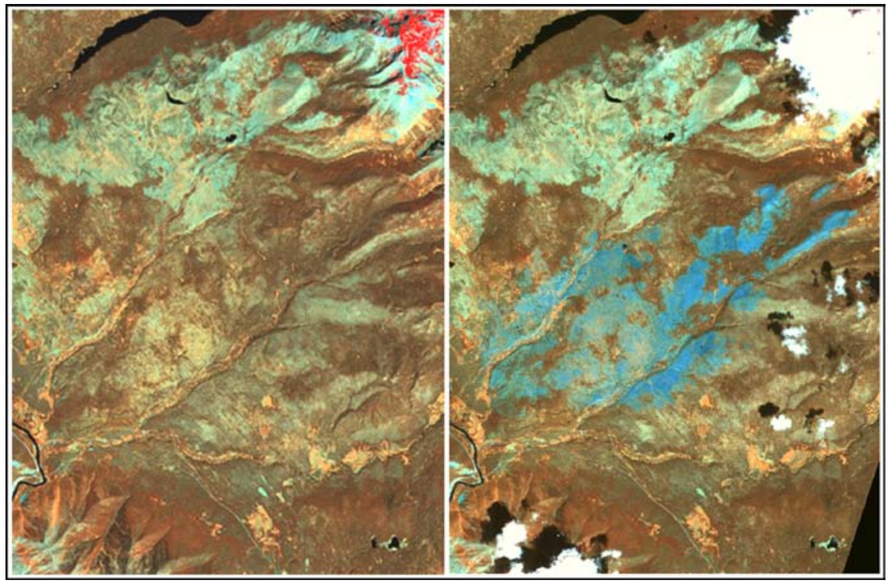

Figure LA-4—These images show the Anaconda burn area, on the west side of Glacier National Park, on 10 July 1999 (left) soon before the fire, and on 25 June 2000 (right) about 9 months after the burn. The light area above is a 1994 burn still evident on the landscape. Clouds appear as bright white in the 2000 image. Knowledge of prefire conditions allows one to gauge severity through change detection techniques and explore relationships between burn patterns and vegetation structure and composition.

To be applied, Landsat data must be statistically related to particular features of interest on the ground. One must determine target characteristics that are important and find ways to measure those that are complementary with the sensor (fig. LA-5). Ground measures provide the basic way to gauge usefulness and to understand the meaning of results. Thus, to assess burned areas, a field-based sampling strategy has been developed to be compatible with the resolution and spectral characteristics of the Landsat TM/ETM+ data. Though relevant to signals relayed from satellites, field information also can be used independently, where applications on the ground call for broad-area coverage or synoptic levels of detail.

The FIREMON Landscape Assessment methods were developed along the lines of: 1) optimizing satellite-derived information; 2) matching ground-based methods to the constraints of remote sensing; and 3) standardizing procedures to meet the needs for comparable results and implementation. The following sections in this chapter cover the three interrelated elements of the approach.

Definition of burn severity. Adapted to moderate resolution, mesoscale perspectives, the definition influences how we interpret severity on the ground. It is the basis for understanding fire effects at the landscape level, encompassing perhaps many types of communities over large areas. Definition is critical to correctly apply methods, use information appropriately, communicate results, and avoid misconceptions. To some extent, this may differ from concepts of severity based on individual trees, small-area microplots, or subsurface evidence of heating.

Ground measure of severity (Burn Index, BI). The protocol is designed to match field sampling with the definition of severity and the characteristics of TM/ETM+ data. The measure is called the Composite Burn Index (CBI). It also can be used for a variety of applications to estimate the general, average burn conditions of stands or communities.

Remote sensing measure of severity (Burn Remote Sensing, BR). This section shows how to process and map burn severity using Landsat TM/ETM+ data. A particular algorithm is used, called the Normalized Burn Ratio (NBR). Pre- and postfire NBR datasets are differenced to isolate the burn from surroundings and provide a scale of change caused by fire. In most cases, the approach reliably separates burned from unburned surfaces, and optimally identifies a broad gradient of fire-effect levels within the burn.

The LA Cheat Sheets follow the BI and BR sections, and a field form is provided at the end of the BI section. Additional techniques specific to the LA methods are described in the **LA How-To** section in this chapter. The **LA Glossary** follows the **How-To** document.

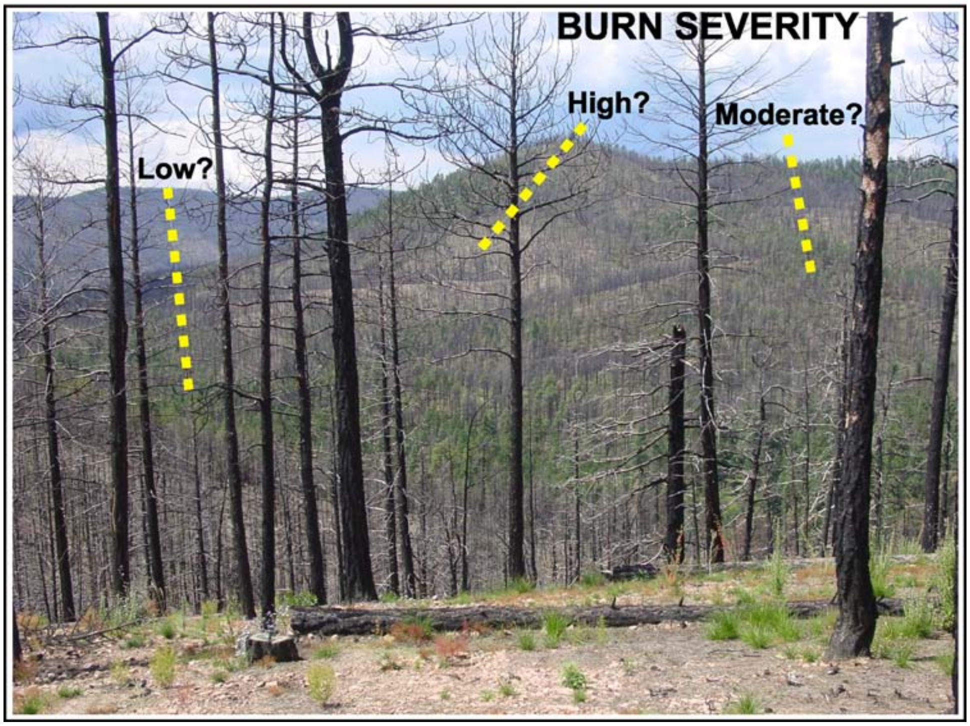

Figure LA-5—Fire creates heterogeneity on the landscape. How does one define severity so this mosaic of effects can be mapped across broad regions? Viewed from space, features on the ground become aggregated across multiple levels to make up the spectral signals received by satellite. Upper canopies are important, but so too are lower strata that may show through the canopy or become more prominent after fire. To assess severity, key features within each stratum are evaluated that have relevance to ecological effects on the site as well as potential for contributing to the satellite signal.

DEFINITION OF BURN SEVERITY FOR LANDSCAPE ASSESSMENT

Admittedly, there is still some discrepancy in the way researchers and managers use the term "burn severity." In this section we clarify how we intend to use it so at least one might better understand our discussion regarding Landscape Assessment of burns. Whether or not these concepts become standard practice depends on repeated trial and acceptance, but we hope this chapter contributes to more discussion and common understanding of the issues involved.

Some of the discrepancy arises from inconsistency in the combination of the relevant terms: *fire, burn, severity, and intensity*. It is useful, therefore, to first define these for LA methods. The meanings we aim to convey are brief excerpts taken from the dictionary, followed by nuances imparted in the context of wildland fire.

FIRE (n). The phenomenon of combustion manifested in light, flame, and heat. The period of active flaming and smoldering.

BURN (n). Injury, damage, or effect produced by heating. The result(s) of fire, also an area where fire has occurred in the past.

INTENSITY (n). The strength of a force, or the amount of energy expended. The level of heat produced by fire.

SEVERITY (n). The quality or state of distress inflicted by a force. The magnitude of environmental change caused by fire, or the resulting level of cost in socioeconomic terms.

Based on the definitions it seems reasonable to apply the following two terms:

FIRE INTENSITY: The magnitude of heat produced by fire is an empirical measure that gauges the fire's status during combustion. This is commonly defined in reference to fire line intensity, which equals energy output per length of fire front per unit time. It may be measured by thermocouple readings in time series, as in experimental situations, or more commonly on wildfires, in proportion to observed flame length and rate of spread. Fire intensity may be divided into two heat components: downward penetration into soil, and upward transfer to vegetation and the atmosphere. These depend on residual flame time and are a function of fuel and weather characteristics. An analogy to fire intensity is storm intensity, which uses such parameters as wind speed and precipitation rate to describe the strength of a storm.

BURN SEVERITY: Socio-economic impacts associated with fire can be measured directly in terms such as cost of suppression, cost of rehabilitation, property loss, or human causality. For this discussion, however, we focus on the degree of environmental change caused by fire. This result of fire is the cumulative after-the-fact effect of fire on ecological communities that compose the landscape. An analogy to burn severity would be storm severity, which refers to the damage or outcome left in the wake of the storm. For example, you might say an intense storm resulted in severe consequences. The ecological criteria to judge burn severity differ, naturally, from those of storms. Here we are talking about physical and chemical changes to the soil, conversion of vegetation and fuels to inorganic carbon, and structural or compositional transformations that bring about new microclimates and species assemblages. The scope includes all degrees of effect, ending with the most extreme where essentially all aboveground organisms are eliminated, and the community must regenerate from "ground zero."

Of the remaining two terms, "burn intensity" seems least sensible and should be avoided. "Fire severity," though, does make sense, so long as one clearly understands it references conditions left after fire. We have simply chosen to use the term "burn" with severity, mainly to reinforce the notion of an area where fire occurred some time in the past.

Discussion of Ecological Burn Severity

No common standard has emerged to measure burn severity ecologically. There may be, in fact, many valid ways to view burn severity, depending on the scale and the particular means available to measure it. On the other hand, a fundamental concept of burn severity—as we suggest here as a magnitude of change—may lead to designing measures of severity that are at least compatible over multiple scales.

How investigators choose to measure ecological burn severity is closely linked to the objectives of burn evaluation. In most cases, it is scale dependent, so definitions reflect the detail and complexity of systems described. You may be interested, for example, primarily in only one factor, such as potential for herbaceous recovery. In that sense, severity may be understood and scaled directly by a single measure, such as depth of charring or scorching into soil, and this measure may be well suited for evaluating small areas, but the method would be difficult to implement over large areas. There are literally thousands of individual ecological components that might be used to indicate severity. To some extent, each species potentially responds in a unique way to fire, and depending on objectives, change in abundance of just one species may be most relevant to describing severity.

In landscape ecology, however, we tend to look at burn severity holistically, such that it represents an aggregate of effects over large areas. This enables you to map and compare whole burns composed of many communities that occupy various topographic, climatic, and edaphic situations. Here, severity is three dimensional, spread over multiple components and strata of the community and across units of area that almost always display considerable heterogeneity. The overall severity of the site, then, can be viewed as the average of all that variability. Besides specific ecological consequences such as tree mortality, burn heterogeneity or patchiness is also a primary variable of interest. It reveals large-scale interactions of fire behavior with the environment (useful for fire modeling) and influences the kind and rate of recovery (useful for ecological projections). At the same time, it is advantageous for assessment of burns to retain some level of information about individual components so you can break those out to evaluate specific conditions.

In a broad sense, the consequences of fire in a particular area are governed by short- and long-term processes, so overall severity is an amalgamation of factors. The most immediate effects are on the biophysical components that existed on a site before the fire. Downward and upward heat transfer generated from fire intensity directly causes those effects. The amount of downed woody fuel consumed, or the biomass of living canopy that was killed, are examples of this, and we refer to it as the short-term severity or first-order fire effects (fig. LA-6). Those effects, though, are dependent on sensitivities of the components where fire occurs, which are far from equal across the landscape. For instance, it is well known that some species have adaptations that make them more resistant to fire than others. The implication is that the same fire intensity can produce different degrees of initial burn severity, depending on the community's prefire composition and structure. Thus, severity likely does not vary in parallel with intensity, especially through low-to-moderate ranges, though the two variables are obviously related. At highest ranges of fire intensity, however, even fire-adapted species are likely to be severely impacted.

Beyond that, the longevity of impacts and the nature of postfire responses are influenced by a number of locally unique conditions, including:

- The kind of seed bank species present, and whether or not they are able to mature under fire-altered microclimate and soil.
- Proximity to adaptive seed sources from unburned areas.
- Localized site properties, such as slope, aspect, and soil moisture-holding capacity.
- Successional pathways and the successional stage when the community burned.
- Subsequent climate, which may differ from historic climate existing when the prefire community became established and matured.
- Secondary ecological effects initiated by fire, such as erosion and mass wasting.

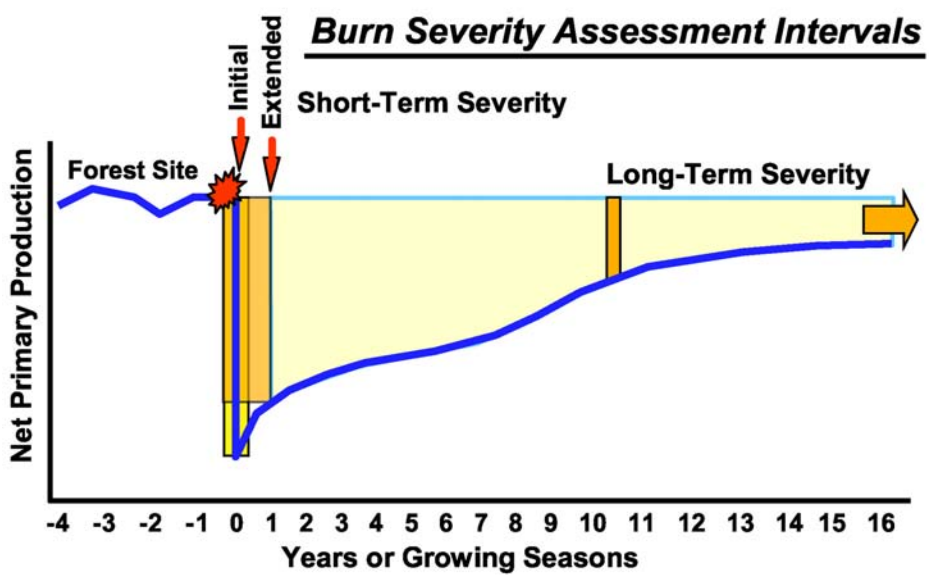

Figure LA-6—A hypothetical 30 x 30 m forest site experiences a fire. Short-term severity reflects change to prefire community components (vertical bars). Long-term, it reflects both that change, plus unique site conditions that prevail into the future. In reality, many response variables are aggregated over many strata of the forest to determine the overall severity on the site.

These combine with initial effects on established components to shape *long-term severity* (fig. LA-6), the magnitude of long-term change brought by fire. In most cases those local circumstances can be estimated, or at least inferred for an area, so it is really the spatial variation in short-term severity that must be determined. If that is known, then projections about long-term severity can be worked out. Thus, in the LA methods, we focus on first-order effects and attempt to define and map severity as it relates to the *magnitude of change to components existing at the time of fire*. To an extent, that includes near-term vegetative survivorship of the next growing season, which incorporates recovery and delayed mortality of burned vegetation as major expressions of short-term severity.

The measure of severity across landscapes, we propose, is first a combination of factor effects within strata, and then a combination of strata effects within communities or subregions of the burn. Such may be difficult to conceive, but if the degree of change is the focus, one can envision a numeric scale with zero (no change) being the starting point, and some positive number as the highest possible amount of change. We can apply the same scale to each stratum of the landscape, and combine those to derive an overall measure for an area. At the lowest level, factors within strata are rated independently. Then, factor values are averaged per stratum, and likewise, strata are integrated into higher levels to ultimately derive the severity of the whole community. The criteria may differ by stratum, but the scale applied to all is the same. It is the full range of change between no effect and greatest possible effect (due to fire), which forms a common denominator. The measure of severity, then, is a consistent numeric scale gauging the amount of change. It may represent a single factor or a composite of multiple factors, depending on intent.

To successfully assess burn effects across landscapes, two methods are required, one for remote sensing and one for field validation and calibration. If comparable remote sensing data are available from before fire and after fire, magnitude of change can be determined empirically, as described in the **Remote Sensing Measure of Severity: The Normalized Burn Ratio** section later in this chapter. Thus, the proposed definition of severity can fit relatively easily with available remote sensing technology, so long as guidelines on timing are followed. For field estimation, however, you must judge how much change occurred relative to prefire conditions for the individual rating factors and that can be difficult, given a typical lack of prefire data for most burns. Also, it is not ordinarily the case that significant portions of many large burns can be visited within 1 year after fire, and alternative information, such as aerial photography, is rarely available both from before and after fire. Consequently, you must rely heavily on expert knowledge and judgment when gathering field data.

Ways to sample for ecological severity in Landscape Assessment are presented in the **Ground Measure of Fire Severity: The Composite Burn Index** section in this chapter. The breakout of strata and the rating factors for the CBI are discussed in detail in the **Field Documentation** section. Basically, they boil down to phenomena we can observe. Some pertain to the amount of organic material consumed and characteristics of residual inorganic carbon and ash, while others address short-term potential for vegetative regeneration and mortality. The amount of heating is also inferred by estimates of scorching, or changes in amount and color of exposed mineral soil. The selected factors are only a manageable subset of all the possibilities for judging severity. They were the ones that collectively seemed most recognizable and significant, while being most relevant to remote sensing and radiometric response.

GROUND MEASURE OF SEVERITY: THE COMPOSITE BURN INDEX

These methods are used to derive index values that summarize general fire effects within an area,that is, the average burn condition on a plot. They are designed for moderate-resolution remote sensing applications, assuming a landscape perspective of entire burned regions. As such, plots are fairly big and widely spaced (>90 meters apart). Field data are relatively quick to collect (about 30 minutes per plot), relying mostly on ocular estimation and judgment. This allows a representative number of plots to be sampled effectively over large areas. The primary task is to encompass the range of variation found within burns, covering as many fire effects and biophysical settings as possible.

A characteristic of sampling is that average conditions of many factors are considered across multiple strata to derive the severity value for a plot. As such, the approach has been named the Composite Burn Index, or CBI. It logically parallels the way Landsat satellite sensors average all features within a pixel to record the multispectral brightness values used to model burn severity.

CBI information is not solely limited to remote sensing, however. Field data can stand alone for general burn assessment, as a way to summarize conditions exceeding a few hectares. Methods work at stand or community levels to estimate the combined severity of individual factors. Data may be useful for reconnaissance, rapid assessment after burning, planning rehabilitation, documenting results of prescribed burns, or any activity where burn information needs to be gathered relatively quickly over large areas. Other methods within FIREMON address smaller scale sampling for detailed fire effects on individual components of a community. Those can complement the CBI when more site-specific information is needed.

The landscape sampling design is hierarchical and multilayered. Each stratum of a vegetative community is evaluated independently by several criteria and given a rating. Scores are decimal values between 0.0 and 3.0, spanning the possible range of severity between unburned and highest burn effect. Scores may be combined (averaged) to yield aggregate CBI ratings for the understory, the overstory, and the total plot. Table LA-1 shows the three composite levels (lettered) and five strata (numbered) currently used. The total plot CBI comprises all five strata, when all strata are present. When plots do not contain all strata, those missing strata are simply not counted. Ratings may be reported separately by strata or in their composite forms, depending on objectives.

What Do CBI Values Mean?

The CBI provides an index to represent the magnitude of fire effects combined across all strata per sample area of a community. Ratings incorporate such factors as condition and color of the soil, amount of vegetation or fuel consumed, resprouting from burned plants, establishment of new colonizing species, and blackening or scorching of trees. As a continuous numeric value, the CBI is useful for correlation with environmental variables, such as plant productivity or fuel loading, and is well suited to communicate to managers and researchers the salient attributes of burns. For example, you might calculate a CBI score of 1.4 for one area and over time compare vegetative recovery there to another area with a CBI of 2.3. In addition, the CBI may be stratified into ordinal levels as a basis for tabulating area statistics or aggregating effects. You then may report impacts in terms of low, medium, and high severity merged over multiple burns, for example.

The CBI attempts to answer how ecologically significant the consequences of a given fire are, or how much fire has altered the biophysical conditions of a site, by providing the numeric scale for gauging such changes. CBI is not uniquely weighted for different community types. Rather, by defining severity, it attempts to gauge the magnitude of change from prefire conditions; thus, it should provide comparable values regardless of community type, location, or time. It is inherently related to prefire conditions and not an absolute value, like weight of fuel per unit area. A distinction is made that a given fire intensity can produce variable degrees of burn severity, depending on site or vegetation characteristics. For instance, low to moderate fire intensity will likely generate more severe consequences in stands of thin-barked tree species such as spruce, than on thick barked species such as ponderosa pine. The CBI should register such differences appropriately, yielding higher values in the spruce stand than in the pine

Table LA-1—Three composite levels (A–C) encompass the five strata level (1–5). CBI scoring is completed for each strata and averaged to the desired composite level.

A. Total plot	B. Understory	1. Substrates
		2. Herbs, low shrubs and trees less than 3 ft (1 m)
		3. Tall shrubs and trees 3 to 16 ft (1 to 5 m)
	C. Overstory	4. Intermediate trees (pole-sized trees, subcanopy)
		5. Big trees (upper canopy, dominant/co-dominant trees)

stand, even though the fire intensities for both were about the same. Thus, CBI does tend to reflect a community's sensitivity to fire when fire intensity is constant.

A second example is worth considering. In herbaceous communities, fire intensity is normally lower than in forested areas, due to less fuel loading and stratification. Consequently, burn severity is usually less and more ephemeral than in a forest. In most cases, fire actually enhances productivity of herbs through the first or second growing seasons after fire. This is partly a response to nutrient cycling and reduction of aboveground competition, while belowground heating is low and minimally damages roots or rhizomes. In such situations, CBI is predominantly based on the lower two strata of the understory, yielding low but positive overall severity scores. It rarely attains the levels observed in forest burns, and it reflects the true nature of low fire impacts to herb communities. It is not a relative measure considering herb communities alone. Enhanced productivity, above 100 percent of what it was before fire, is presently being evaluated for CBI. Currently, it is captured by variables in the herb and shrub strata, but is not yet averaged into CBI ratings.

Keep in mind, CBI is geared to correlation and validation of 30-meter Landsat data. It helps answer the question of satellite mapping performance for large burned areas. Hence, emphasis is on a large plot size, multistrata average conditions, covering the range of effects with sufficient replicates, and sampling broad areas efficiently.

Sampling for the Composite Burn Index

Time since fire is relevant to how factors appear when a plot is sampled. Therefore, it is essential to plan field work for specific objectives, and to enter the "fire date" on the field form so you can track the timing of field data. If you are interested in short-term severity (first-order fire effects), the optimum time for fieldwork is during the first postfire growing season. This would correspond with the timing for *extended assessment*, which is the primary reference point for change from prefire conditions, as it reveals survivorship potential and delayed mortality. That timing naturally varies by ecosystem, however. It can be as long as 9 to 11 months in relatively cold climates, or as short as a few weeks in sub-tropical regions.

If plots are visited soon after fire, as in *initial assessment*, many effects will be evident, but ability to estimate survivorship and delayed mortality will be diminished. New seed germination and resprouting likely will be missed, as will effects on trees stressed but not immediately killed by fire. Soil properties may also be obscured by ash that has not had time to wash off. A solution for initial assessment may be to simply omit some factors from consideration, but that could weaken the validity of CBI. At the least, detective work may be needed to make reasonable ratings of such questionable factors.

If plots are visited beyond the first growth period after fire, short-term effects become increasingly obscure. Data then reflects elements of recovery that may largely depend on postfire climate, soil, or other factors, and only partly on the first-order fire effects establishing a site's new ecological starting point. Intervening litter fall and prolonged growth, for example, may lessen the apparent magnitude of short-term severity. Under these circumstances, assessment may require calibration of observed responses back to what they were like one growing season after fire. Counting back the annual nodes of growth on shrubs, for example, can help determine the resprout status in previous years.

On the other hand, revisiting plots several years after fire provides useful information about long-term severity and recovery rates. Imagery and plots can be compared if they have similar sampling intervals since fire. A time-series of CBI data can be used for multiple change detection experiments in remote sensing and to help verify predictions made about severity from initial and extended assessments. The timeframe may be compressed in semitropical regions to perhaps as short as 1 year, and still be practical for monitoring prescribed fire effects. For such objectives, a plot can be read straight up as it appears at the time of sampling. Some factors may be relatively static, such as percent of black tree canopy, while others may change markedly over time, such as percent of trees felled or shrub and sapling regrowth. Record "fire date" on the CBI form and do not lose sight of time as an important variable in analysis.

We recognize that ground data might never be available on many burns, given the constraints of time, funding, and logistics. Therefore, we expect some remote sensing results to be calibrated or validated with field data collected from different areas. We presently see no problem with this, so long as the burns are similar and remote sensing data are acquired with similar timing. Once a number of burns have been sampled in a region, statistical confidence in the remote sensing results should increase to a point where the need for new ground data should diminish. It can continue to be collected, but only to spot check results. That is, in fact, one goal of the whole process, so field time and expense can be minimized, without sacrificing reliability and availability of burn information. In all cases, the level of validation should be documented in the FIREMON Metadata table.

Sample Design and Site Selection

For remote sensing applications, we prefer a stratified sampling design that attempts to represent the full range of severity with equal sampling effort across it. The main objective is to analyze statistical association between burn severity observed on the ground and the variation derived from satellite data. There is no need for CBI samples to estimate the spatial composition of the burn itself because the remote sensing product will eventually provide a complete tally of the entire "population" of burned pixels. Thus, the sample of CBI plots only calibrates and/or validates remote sensing with less necessity for strict spatial randomization.

In most cases, depending on burn size and complexity, 50 to 100 plots per burn are adequate. This should yield suitable sample size to determine how well remotely sensed severity correlates with field measures. If several burns from the same year are being assessed in one area, plots can be distributed over multiple burns. If total burn area is larger than about 2,500 acres (1,000 ha), the number of plots is somewhat independent of burn size. Large burns tend to exhibit an adequate range of severity in proportional area sufficient for sampling. On the other hands, smaller burns are typically not as diverse and may be covered by as few as 20 to 40 plots. To spatially stratify the sample, limit plot selection to suitable locations defined by accessibility and data-content factors. Ownership, topography, and distance to roads and trails are key elements when overlaid in a GIS to mask out unsuitable areas.

If the delta NBR (dNBR) is available (see the **Remote Sensing Measure of Severity: The Normalized Burn Ratio** section), additional stratification based on the severity level and the amount of localized heterogeneity may be warranted. You would attempt to draw locations from small areas that show minimal spatial variation in dNBR. Such stratification can be based on the 3 x 3 pixel matrix of dNBR for each pixel being within a range of about 0.15 dNBR of its neighbors (maximum–minimum–≤ 0.15), or 150 if dNBR is scaled by 10^3. Some experimentation may be necessary to arrive at minimum variation that offers sufficient areas for sampling, with the cutoff being as low as practical. One may find enough sample pixels, for example, with the cutoff for local variation being set as low as 0.10 dNBR (100 if dNBR is scaled by 10^3). Pixels satisfying that requirement would tend to be located in areas of fairly homogeneous severity, and would generally represent surrounding pixels. Sampling those pixels would lessen problems associated with georectification accuracy of satellite imagery and locational error in the field. It would help ensure that plots were sampled from the intended areas. It would also help associate a given CBI value with the appropriate dNBR value in analysis. Moreover, it would reduce the chance of vastly dissimilar or nonrepresentative nearby pixels from affecting the site through autocorrelation of reflectance from adjacent pixel values. Likewise, such pixels would have less chance of corrupting a local dNBR average, if a pixel-neighborhood approach were used to compare dNBR to the CBI.

After suitable sample areas are delineated, attempt to randomly draw roughly equal numbers of target locations from each of the general ranges of severity: unburned, low, moderate-low, moderate-high, and high. Plan for about 10 to 20 plots in each of these levels. Unburned sites will be visited only to verify that none of the plot burned, so effort per plot should be minimal in those cases. A histogram of pixel dNBR frequencies within the burn can be used to check whether or not selected locations adequately sample the range of variability within the burn. At this stage, the severity levels are just based on best available knowledge. They are likely to change slightly during the course of the survey, so anticipate some adjustment in sample target areas as work progresses.

The way locations are selected within the stratified sampling area can be either random or nonrandom. Stratified random locations raise fewer doubts from independent reviewers and may be more appropriate for some statistical analysis. There is often a trade-off in effort and doable sample size with spatial randomization, however. Objective but nonrandom selection gains substantial field efficiency by the ability to group plots near one another or along routes traversable in a day. More plots can be done that way, and sampling can often achieve adequate representation with fewer plots across the total range of severity than can random locations. Furthermore, judgment in the field can be exercised to pick up additional plots while walking through large areas that seem to represent certain burn conditions but were overlooked in preselection.

Spatially random design without stratification is not advised in large or remote burns because access to many sites will be prohibitively time consuming, and many will end up being excluded because they fall in highly heterogeneous or otherwise unsuitable areas. Moreover, randomization leads to sampling the levels of severity in proportion to the area covered within each burn, not in equal numbers per severity level, and each burn is unique in regards to its spatial composition of effects. Total randomization generally requires more plots than stratified random or nonrandom sampling in order to collect enough plots from severity levels of limited distribution within a burn. Thus, random sampling would only be called for if one hopes to represent the entire population of burned pixels from the sample or attempts to estimate the spatial composition of the burn. By contrast, the objective here for CBI plots is to represent all levels of severity more or less equally for the limited purpose of ascertaining the nature of the relationship between severity on the ground and the magnitude of change detected by dNBR.

Keep in mind that the greatest expense of time is usually getting to sites in the field. It is best to err on the side of collecting more sample plots than to get fewer plots while trying to reach remote and hard-to-access areas of the burn.

Plot Layout

In the field, navigate to preselected target areas by GPS and locate the plot center. In most cases that will be at the preselected coordinates. However, at times that location may not be suitable for one reason or another. Try to select locations that 1) represent the range of variability found at the site and 2) fall within relatively large homogeneous areas, preferably 200 x 200 ft (60 x 60 m) of basically the same fire effects. This allows a plot to be placed somewhat centrally in the larger area, to be representative yet not too close to adjacent areas exhibiting different fire effects. "Too close" depends on remote sensing resolution. Here we are considering 30-m Landsat data, so try to stay at least 150 ft (45 m) from the edges. Plots should be spaced at least 300 ft (90 m) apart. If more than one plot can fit within the target area, attempt to sample that as well, depending on time constraints. Though an area may look patchy or mottled with burn, it may still represent a level of severity that is characteristic of the burn, especially where impacts are light to moderate. In those cases, look for areas with the same degree of small-scale patchiness throughout. Remember, the plot and the Landsat data are integrating surface characteristics over about 0.25 acre (900 m^2), so try to envision the land from that perspective when in the field.

In some validation studies, it may be necessary to have a subset of preselected plot locations that are *never* deviated from in the field. In those cases, proceed to locate the plot center as precisely as possible at the specified coordinates. Attempt to read the plot even if it seems unacceptable due of edge effects, for example, and note such problems on the CBI form. A decision to keep or reject the plot can be made later. If a more representative site exists nearby, it may be worthwhile to add another plot there since the crew has already made the effort to reach the area. That plot could be used for calibration even if it may not serve in validation.

At plot center, set the GPS to coordinate averaging mode, and let it acquire data over about 10 minutes or so. Record the GPS location in UTM coordinates to the nearest meter, noting the zone number, geodetic datum, and the amount of error. Mark the plot center so it can be identified temporarily while taking plot data. From plot center, stretch two tapes out to locate the plot perimeter with a 49-ft (15-m) radius or 98-ft (30-m) diameter. In open plant communities, it may be sufficient to just lay two tapes on the ground crossing at 90 degrees at plot center. Mark the plot perimeter at the end of each tape with flagging so that the boundary is discernable. At times, if understory effects are relatively complex or the plot is too difficult to walk through, one can use a nested 66-ft (20 m) diameter plot for the understory, while keeping the 98-ft (30-m) diameter plot for the overstory. If 66-ft (20-m) understory and 98-ft (30-m) overstory plots are used, the two different plot sizes need to be marked. If you do not plan to return to the plot within a short time, remove all flagging before leaving. Recorded GPS coordinates will serve to relocate the plot if revisited in the future.

Plot Sampling, Using the Field Form

The **LA data form** (provided in the **Field Documentation** section of this chapter) cues all information needed to calculate CBI values for the plot. Each stratum present on the plot is evaluated independently by a number of factors. The basic data are severity scores in decimal increments (0.0 to 3.0) that express the magnitude of fire's impact on the individual rating factors, such as litter and duff consumption. The criteria used to score each factor are given in more detail in the **Field Documentation** section, but they generally correspond to break points along an escalating scale of effects. For example, if the proportion of tall shrub resprouting is around 90 percent, you would assign that factor a score of 1.0; for 30 percent regrowth the score would be 2.0.

It is beneficial to work in teams of two or three. The crew can either evaluate the plot independently or together, but at some point before recording final ratings, try to reach consensus on each factor. It is beneficial to compare impressions and discuss why each score was given. This process aids consistency, adds confidence in the ratings, and generally leads to better understanding of fire ecology on the site. The team may consider understory criteria first and then the overstory. With a day or two of experience, the team can complete a plot in about 30 minutes (not including travel time to the plot).

Take a while to become familiar with the strata on the plot and the factors used to rate each stratum on the **LA data form**. Refer to the **LA cheat sheet** at chapter's end, and especially to the definitions of strata and rating factors provided in the **Field Documentation** section. Take time to walk over the whole plot, looking for clues that point to particular levels of burning. For example, dig through litter and duff and examine stems focusing on amount consumed, depth of charring, and survivorship. Consider the condition of tufts of grasses. Charred bark or buds may conceal living tissue with potential for regeneration, even though elapsed time may not be sufficient for that to occur. Also, remnant woody material on burn plots usually indicates previous vegetation structure; look for the snags or stubs of former trees and shrubs. Finally, it helps to compare nearby unburned areas to gauge what might have been present on the plot before burning; base similarity for comparison on topographic factors, soil type, and the density and size (age) of trees. Keep this in mind when traversing unburned terrain on the way to burn plots.

Once comfortable with general understanding of the plot, enter the plot descriptive information at the top of the CBI form. Then determine and enter the amount of burned area within the 98-ft (30-m) plot (the percent of plot area showing *any* impact from fire). Make that determination also for the nested 66-ft (20-m) plot if it is used. Area estimators at the bottom of the form can be used throughout the exercise to help resolve percent cover in a plot. Also, for each stratum there are a few variables to describe prefire conditions. They are entered early on to serve as benchmarks for estimating the amount of change called for later in some severity factors. These preliminary entries are important, so please make every effort to record them.

Proceed down the data form, stratum by stratum, scoring each factor between 0.0 (no burn effect) and 3.0 (highest burn effect). Factors are designed to take decimal scores, so you may score a 2.8, for example, if you feel the condition is not quite a 3.0 but definitely more than 2.5. It is important to decide where a rating falls in reference to average conditions over the whole plot. In other words, if there is patchy distribution of both moderate and low burn effects, average those aerially together and mentally determine an overall score. It likely will be somewhere in the middle, depending on proportions of each level observed across the plot. Scores generally reflect the degree of change from the preburn state, for example, the proportion of fuel consumed. If herbaceous cover was sparse before fire, for example, you would not necessarily give a high score to sparse herb resprouting observed after fire. It would depend on how the herbs are doing relative to how dominant they were before fire.

If some factors (or strata) do not apply to the plot, then do not count them. On the data form, however, you should note why the factor was not assessed so people do not think you simply forgot to record it. The entry may either be "not applicable" (N/A) when the rating factor is insignificant or not present, or "uncertain" (UC) when the factor may be present, but one cannot make a reasonable determination about it. Such fields are ignored during analysis. For example, the plot may have big trees but no intermediate trees. Then the intermediate trees simply would be N/A and not be rated, so the overstory CBI would be based on just the big trees. Do not score nonapplicable factors as zero. A zero score means that a factor was present and it was ratable at a level determined to be unaffected by fire. Zero ratings *do* get averaged into CBI scores. The N/A and UC codes cannot be entered in the FIREMON database. When entering data in FIREMON leave blank any fields where you recorded N/A or UC. An explanation of why certain fields were not assessed can be entered in the comments section on the data entry screen.

When all factor scores are entered, calculate an average rating for each stratum and the CBI for understory, overstory, and total plot. That is done by adding up scores within each hierarchical level and dividing by the number of *rated* factors. To get overstory CBI, for example, total intermediate tree and big tree scores and divide by the number of factors rated for both intermediate plus big trees. For total plot, add up all factor scores and divide by total number of scores rated in all strata. Note, when entering data using the FIREMON software, CBI values are calculated automatically by the database, which helps to double check scores entered on the field form.

Before leaving a plot, review the CBI ratings. See that they make sense and adequately correspond to interpretations of the plot. If not, examine strata ratings; consider and discuss which one(s) may be questionable and why. You will often find that severe impacts in one stratum are mitigated by lesser impacts in other strata. This is an intended result when aggregate CBI ratings are calculated. Differences of a point or less between observers on individual factors usually make little difference in overall CBI ratings. Thus, it generally is not worth adjusting the disparity in single factor scores unless they are quite different after complete CBI ratings have been calculated. Remember, you are interested in cumulative impacts of fire over the vertical structure in a community and over the whole area of a plot. The first impression of a plot may be biased toward obvious conditions in one stratum, but when all strata are considered independently and averaged, one often agrees that the "real" composite effect is different from that first impression.

Finally, enter community notes or comments about burn patterns within the plot. These are important attributes to know in subsequent analysis. Things to consider here include: height and density of the various strata, dominant species present per strata, general fuel characteristics, general microclimate and moisture, topography, evidence of insects or disease, and any descriptors about the burn mosaic. Other comments may refer to the suitability of the plot, for example, if the plot straddles an edge or has signs of postfire disturbance like salvage logging.

There are two reasons to note observations that may not directly relate to the CBI. First, fieldwork is expensive and time consuming, so it is most efficient to gather all potentially useful information the first time and avoid a site revisit by you or others. Second, fire affects many things that may be of interest to others in a variety of disciplines, and it is always beneficial to demonstrate a service to the areas one visits; thus, recording any information that may potentially be useful is encouraged. That may include observations of rare plants or weeds, cultural resources exposed or affected by fire, interesting wildlife sightings (including carcasses), as well as erosion or water quality evidence. It is always good to communicate with local resource and cultural specialists before fieldwork to be better informed on what to look for and to find out what may be of interest.

Field interpretations for the CBI are forced to be a little fuzzy and based on best judgment. They must assess change to a site, usually without quantifiable data on what was there before fire. In addition, some estimated effects are time dependent and may not become manifest for a while after fire. These are just inherent circumstances of burn evaluation. It is much like forensic ecology. Do the best you can, and with experience you will get increasingly comfortable untangling the sometimes puzzling evidence of burn severity.

Plot Photos

It is a good idea to take photos after completing the rating exercise, when you are most familiar with plot burn conditions. There are many approaches to this, but some recommended procedures include the following. Use a high-resolution digital camera, or a 35 mm camera with color slide film, ASA of about 125. Take at least two photos approximately 180 degrees opposite one another, showing the plot center and about half of the plot in each. Avoid taking photos directly toward the sun, especially under darkened forest canopy. Include a signboard for scale and to identify the date and plot number in the picture. As time or objectives allow, take other photos targeting features of interest, such as typical charring patterns on substrates or trees, and regrowth on perennial herbs and shrubs. Try to capture tree canopy effects as well as ground effects. It is also useful for training or presentations to take photos specifically to represent different severity characteristics or fire scenarios, and problems encountered in the field, whether or not they fall on a plot.

FIELD DOCUMENTATION

Strata Definitions

With the CBI, fire effects are assessed somewhat independently within strata because vertical levels in a community have different biophysical components, and multiple levels impart structural complexities that profoundly influence fire behavior. Structure affects how wind shapes fire and the nature of available fuels. Though strata are spatially contiguous, each level may have unique combustible properties and effects may differ strongly between them.

At times in the field, one may find vague or discontinuous boundaries between strata where distinctions are not always clear cut. In such cases, try to reach consensus on what is included or excluded from each stratum and be consistent from plot to plot. If distinctions between some strata cannot be resolved, it may help to simplify the overall structure; try combining strata, or drop one out. Even if only one factor in a stratum appears to be applicable, continue to score that stratum. The main objective is to make reasonable interpretations on one to five factors within each stratum, and then to combine those to derive composite ratings that summarize severity over the overstory, understory, and the total plot. The goal is not so much a high degree of precision in rating a specific factor, as it is a consistent summary rating of severity that aggregates a variety of burn effects over multiple levels of the plot.

The strata listed below are commonly identified in a complex forest community, segregated principally by the vertical space they occupy. Their arrangement and component parts determine, to some extent, the character and connectivity of fuel, variation in flammability, and timing of seasonal drying. When evaluating burn severity with the CBI, fuel and fire behavior relationships are emphasized while strata species composition is less important. Because species may exhibit multiple life forms and occupy several strata, consider primarily where individual plants or other materials fit within prefire community structure.

Strata hierarchical structure

A. Total plot (overall)

   B. Understory

      1) Substrates

2) Herbs, low shrubs and trees less than 3 ft (1 m) tall

3) Tall shrubs and trees 3 to 16 ft (1 to 5 m) tall

C. **Overstory**

4) Intermediate trees (pole-sized trees, subcanopy)

5) Big trees (dominant/codominant trees, upper canopy)

Substrates—Inert surface materials of rock, soil, duff, litter, and downed woody fuels. We include just the surface characteristics of soil, even though soil in general could be broken into substrata on its own. This is an artifact of remote sensing objectives with emphasis on understanding changes to surface reflectance. Exposed soil is considered soil or rock surface that is visible from eye level and not covered by litter, duff, or low herbaceous cover less than about 12 inches (30 cm) high. Such surfaces that are likewise visible but under taller shrubs and trees are considered exposed soil.

Herbs, Low Shrubs and Trees (less than 3 ft (1 m) tall)—All grasses and forbs, plus shrubs and small trees less than 3 ft (1 m) tall. Herbs are plants that die back to ground level each year. Shrubs retain persistent aboveground woody stems, from which subsequent years' growth develops. Small trees, including tree seedlings, are like shrubs, but typically have only one central stalk and eventually grow to heights far exceeding this 3-ft (1 m) size class.

Tall Shrubs and Trees (3 to 16 ft (1 to 5 m) tall)—Shrubs and trees generally greater than 3 ft (1 m) and less than 16 ft (5 m) tall. If trees or shrubs are between 16 ft (5 m) and 25 ft (8 m) tall, decide which stratum the life form fits best. They could be scored with intermediate trees, but only if they are distinctly treelike and have characteristics of other intermediate trees. When there is question between this stratum and intermediate trees, look at the community at large, beyond the plot if necessary, and consider whether there really are two strata with one being distinctly taller and over the other. If not, then in most situations you would elect to score only one stratum. Also, consider the life form, and whether there is dense branching that extends nearly to the ground such that fire behavior may be influenced by that in particular ways. This occurs on both counts for many pinyon/juniper communities, for example, where they would be scored for tall shrubs and trees 3 to 16 ft (1 to 5 m), but not for intermediate trees.

Intermediate Trees (pole-sized trees, subcanopy)—Trees occupying space between the tall-shrub/tree layer (3 to 16 ft) and the uppermost canopy; generally 4 to 10 inches (10 to 25 cm) DBH, and 25 to 65 ft (8 to 20 m) tall. If trees of this size are the uppermost canopy, then consider them as intermediate trees while not counting a big tree stratum. This stratum may itself be of stratified heights, with crown tops extending into the upper canopy. Still consider, however, that they are intermediate trees if they receive little direct sunlight from above. Actual size of the intermediate trees is relative to height of upper canopy and may vary from community to community.

Big Trees (dominant, and codominant trees, upper canopy)—Dominant and codominant trees that are larger than intermediate trees. They occupy the uppermost canopy and usually receive direct sunlight from above. These tree crowns form the general or average level of the upper canopy, while some individuals may extend above that.

Understory—This region comprises substrates, herbs/low shrubs/trees less than 3 ft (1 m) tall, and tall shrubs/trees 3 to 16 (1 to 5 m) tall.

Overstory—The region above the understory, consisting of intermediate and big trees.

Total Plot, or Overall—All strata of the plot combined.

Note: Composite scores reflect only those strata that existed before fire. As a rule, strata that are not applicable on a plot cannot be rated and are not considered in the composite ratings. If a plot contains no trees, for example, then only the first three strata would be rated. In that case, we would consider the assemblage an "understory" (even though an implied "overstory" is missing), and use only the combined understory factor scores for the overall rating. The hierarchy intends to accommodate structurally complex communities, while not requiring the presence of all strata.

Initial Summary of Area Burned

Percent Plot Area Burned: Before examining the individual severity factors within strata, record the percent surface area showing *any* impact from fire for the 98-ft (30-m) diameter plot, and for the nested 66-ft (20-m) plot, if that is used for the understory. This always reflects the area of burned substrates and low-growing plants. If there is a rare case with area of burned overstory but unburned understory, count that overstory burn as well, as if viewed from the air. Do not subtract, however, unburned overstory from the burned area of the understory. The percentages are entered early on to set upper limits for rating factors that reference burn effects by proportional area of the plot. These preliminary entries are important, so please make every effort to record them. Note that the 98-ft (30-m) plot covers about two and a quarter times the area of the 66-ft (20-m) plot. Rectangular dimensions are provided at the bottom of the CBI form to help equate plot percentages with ground area as a means of visualizing these quantities.

Prefire Conditions: The CBI form contains a few fields in each stratum for estimating prefire variables such as cover, depth, and density. Complete these as possible, trying to most reasonably represent those specific conditions as they would have appeared before fire. Make sure prefire nonburnable areas within the plot (soil, rock, and so forth) are estimated, so they can be used to calibrate scores later on. Reference within-plot or nearby unburned areas, or evidence such as char heights, amount of charcoal, or number of standing snags. Report cover by percent of plot area, depth in inches, and density of trees as an estimated number of individuals on a plot. The intent is to get general approximate information about prefire conditions. The values will be useful later to possibly weight strata, or to categorize plots and group them in analysis across the potential range of prefire starting points. Remember to take time to compare burned areas with unburned areas to get as good an understanding of prefire conditions as possible. If any prefire information is not feasible to estimate, then enter "not applicable" (N/A) or "uncertain" (UC) on the data form. Do not leave the fields blank on the CBI data form.

Enhanced Growth Factors: Fields for Enhanced Growth are provided on the CBI data form under Herb/Low Shrub/Tree and Tall Shrub/Tree strata. They are used to record whether or not fire has actually enhanced the productivity of herbs, shrubs, or trees above and beyond the level that was on the plot before fire. Productivity can be regarded as amount of green living biomass, in terms of cover, volume, and density. If plots show about the same or less estimated productivity than before fire, then these variables should be entered as not applicable (N/A). If there is cause to believe that a plot shows enhanced growth, then enter the percent productivity that is judged to be augmented by fire, with 100 percent being the same postfire productivity as prefire. An entry of 200 percent, for example, would represent double the estimated productivity that was present before fire, and 150 percent would constitute one and a half times more green vegetation than prefire. Reference similar but unburned areas in or near the plot to gauge the possible effect of fire on enhancing growth.

Rating Factor Definitions

Calculated CBI scores for understory, overstory, and total plot depend mainly on a variety of factors being independently examined and comparably scored. Factors are grouped by strata so field samplers can focus on a particular group of potentially related effects. Strata can then be evaluated in sequence to reflect on whether or not each unit is being scored appropriately. A goal is transferability across regions, and as generically as possible, factors are designed as a framework of components that respond to fire. In addition to the CBI scores, strata-level information can be retained and used in other applications.

It may be tempting to adjust rating factors and criteria to a particular area, but that is not encouraged without carefully considering the entire framework and strategy of the approach. Factors and criteria are designed to balance each other such that ratings do not double-count the same effect or exaggerate one effect over other mitigating effects. In the end, modifications may only add unnecessary detail and diminish the applicability to other areas.

Within strata, the factors that are rated are generally common and relatively easy to observe after fire. Those selected are also ones that may influence surface reflectance directly and be likely elements of a collective signal detected by satellite. As such, rating factors may not include all the effects that may be of interest to fire ecologists and managers (for example, subsurface soil properties). Those other conditions of interest, such as exotic species, can be documented in the Community Notes section of the CBI form.

At present, severity factors are considered equal when averaged into composite levels. In reality, that may not be the case. If one could judge the overall ecological significance of a factor relative to another, factors could be weighted before averaging to improve the measure. For example, it is likely that removal of the tree canopy has longer lasting consequences than removal of litter or fuel from the substrate. However, those relationships are not easily quantified, so, at present, effects are simply considered equal contributors when averaged for CBI severity.

Most Strata Rating Factors are interpreted relative to conditions that existed before fire and not in absolute quantities. This responds to the definition of severity as a magnitude of ecological change, such that the amount of change depends on the state of the community before fire. It is particularly true for all understory ratings, and why the prefire estimates on the CBI form are so important. In addition, all factors are considered in terms of the area of the whole plot. Thus, all areas of a plot are averaged together to derive each rating, adding in unburned spots and mottled burn patterns of varying severity.

Like strata, factors that are not applicable or cannot be resolved in a plot are not rated; they are omitted from that plot's composite ratings. Moreover, if there is much uncertainty about how a specific factor should be rated, or whether it is even relevant to the plot, then that factor should be left unranked. Only the number of rated factors is used to compute averages. If a factor is not rated, enter not applicable (N/A) or uncertain (UC) on the CBI data form. Do not just leave the field blank. As stated previously, such factors are not part of the CBI average, but one wants to know whether these factors were actually assessed and it was decided not to rate them, or just accidentally overlooked and skipped.

Zeros, on the other hand, are valid entries and do get averaged into composite scores. Zeros should be used when a rating factor is applicable and exhibits an unburned condition. A zero represents no detected change in an observable factor.

Field personnel need to use judgment as to whether a factor to be rated has some minimal level of significance as a reference to burn severity on a plot. That pertains to whether or not the factor had enough presence on the plot before fire so as to show representative effects after the fire, or whether it contributed some influence on fire behavior. If, for example, there is only one large fuel item, and it covered an insignificant portion of a plot, then it may not be worth rating. That one piece of wood is not likely to provide much information about severity realized across the plot. Other examples are provided under the specific rating factors below.

If an area has burned more than once in recent years, try to find places where you can compare sites that burned only once in the most recent fire and once in the older fire(s). Look for clues that might identify the age of the evidence, so that when you are on a plot that burned twice, one can separate out the most current fire effects from older ones. For example, the sheen on charcoal dulls with age, and annual nodes on burned shrubs can indicate the years of regrowth since fire. Older burn indicators are not to be used in the evaluation of current fire effects. If reliable indicators to distinguish multiple burns on a site cannot be found, it may be best to reject the plot or skip those rating factors that are not definitive.

If a site has been rehabbed after fire, the added mulch, straw, or woody barriers should not be counted; rather, substrate estimates should be made as if that new material were not present. Any planted and growing vegetation, however, can be tallied where appropriate, such as change to species composition/relative abundance. But rehabbed vegetation should not be included as new colonizers because its response was through cultural activities rather than because of fire. The extent of rehabilitation should be recorded on the data form under Community Notes/Comments.

The primary objective for rating factors is to reach a reasonable cumulative score for each stratum based on field personnel expert knowledge of fire effects. The CBI simply helps to focus that knowledge in discrete directions and provides a standard structure to quantify severity. It is the combination of many ratings, not the precision of any one specific factor score, that gives strength to the CBI.

Substrate rating factors

These factors are rated in relation to the substrate components that existed before fire. Recent postfire additions to substrates, *excluding soil*, are generally not considered in these ratings. That means that you should not count litter, duff, or woody fuels that accumulated after fire. Rather, you should identify and mentally remove that newly fallen material to rate what is underneath. Interpretations should be based on those substrates that were in place at the time of fire.

Make sure to include substrate areas that did not burn as unchanged (such as unburned patches and prefire areas of exposed mineral soil or rock) when estimating average plotwide changes to duff, litter, and soil. Prefire nonburnable area within the plot (soil and rock) must be estimated and entered in the prefire field on the data form so that it can be referred to later on. It is potentially important as a weighting factor for calibration of the dNBR. Exposed soil is considered soil or rock surface that is visible from eye level and not covered by litter, duff, or low herbaceous cover less than about 12 inches (30 cm) tall. Such surfaces that are likewise visible, but under taller shrubs and trees, count as exposed soil.

If there are areas of a plot that cannot possibly burn, such as large prefire exposed rock, then those areas should be treated as unburned. Some caution needs to be exercised, however, because burnable materials, such as litter or vegetation, can cover prefire rock. In these cases, the rock surfaces could have "burned" and they could be treated as burned area within the plot. Charring of rock surfaces and pockets of charcoal can provide clues to that effect. Cobbles and stones less than a 1.5 ft (0.5 m) in diameter may or may not fall in this category, depending on prefire overstory characteristics and to what degree they were covered by litter, duff, or vegetation before fire. Sites generally should be avoided if they contained more than 50 percent exposed rock before fire. Such plots would not reveal much about fire effects and would appear as essentially unburned. There may be occasion, however, to include a few such areas to confirm remote sensing results.

Litter and Light Fuels—Relative amount consumed of small organic materials lying on the surface of the ground, including leaves, needles, and woody material less than 3 inches (7.6 cm) in diameter. All litter is counted even though some may occur under living vegetation. Incorporate nonliving attached basal material, such as dead grass or rosette leaves. In deciduous forest, late season burns are often followed by significant leaf fall, so rate the litter as if the freshly fallen leaves were not present. The same applies to freshly fallen conifer needles. If no light fuels are present, the maximum score, based solely on litter, is a 2.0. Scores above 2.0 need to include some significant portion of light woody fuel consumption. This rating relates to percent change in the litter and light fuels cover estimated at the time of fire, not in relation to total plot area. For example, if litter and light fuels covered 70 percent of the plot and the fire consumed all litter and light fuels, there would be 100 percent change in cover, even though the change only amounted to 70 percent of the plot area. The rating in that case would be a 3.0. Prefire estimates of litter and light fuel cover can be used to weight this factor to determine percent of plot wide change. Litter should probably be assessed as "not applicable" if cover was less than 20 to 25 percent of a plot before fire.

Duff Condition—Relative amount consumed and charring of organic materials that lie beneath the litter and above the soil. Duff is organic material that has undergone considerable decomposition prior to the fire. All duff is counted even though some may occur under living vegetation. Do not consider fine root mass left after duff is consumed to be part of the duff rating. If there was a deep prefire duff layer, then one could use the absence of fine root mass as an indicator of intense fire, which could affect soil structure or chemistry, and influence the soil severity rating, below. Like litter, this rating relates to percent change in postfire duff cover compared to prefire cover; not in relation to total plot area. For example, if duff covered 70 percent of the prefire plot and the fire consumed all duff, the change in cover would be 100 percent resulting in a CBI score of 3.0. Duff should probably be rated as "not applicable" if it is less than 0.25 inch (0.6 cm) deep and covers less than 20 to 25 percent of a plot before fire. At such low occurrence, duff can be treated as part of the Litter and Light Fuels rating factor.

Medium Fuels 3 to 8 inch—This factor gauges primarily consumption of downed woody fuels between about 3 inches (7.6 cm) to 8 inches (20.3 cm) in diameter. Base consumption on the percent of volume or weight lost in relation to estimated plotwide prefire fuel load for this class. Consumption includes conversion of woody material to inorganic carbon (charcoal), as well as the complete loss of woody fuel. Generally, this factor should not be used when such fuels cover less than about 5 percent of the 65-ft (20 m) diameter understory plot (an area about 3 x 5 ft or 10 x 25 m) or when they are distributed in only one localized area of the plot. If there is not enough fuel to separately score medium and large fuels, but the fuel could be scored if size classes were combined, go ahead and score one of the two factors on the form, using the one that seems most common, and make a note to that effect in the comments field. Stumps that existed before fire can be included in this fuel size category or ignored all together, as deemed appropriate.

Large Fuels >8 inches—Includes consumption and charring of downed woody fuels greater than 8 inches (20.3 cm) in diameter. Base consumption on the percent of volume or weight lost in relation to plotwide prefire fuel load for this class. Consumption includes conversion of woody material to inorganic carbon (charcoal), as well as the complete loss woody fuel. This factor should not be used when such fuels cover less than about 5 percent of the 65-ft (20-m) diameter understory plot or when they are distributed in only one localized area of the plot. See note above under **Medium Fuels**, to determine when to combine medium and large fuels. Stumps that existed before fire can be included in this fuel size category or ignored all together, as deemed appropriate.

Change in Soil Percent Cover and Color—Increase in percent cover of newly exposed mineral soil and rock, over and above estimated prefire levels plotwide. Exposed soil is considered soil or rock surface that is visible from eye level and not covered by litter, duff, or low herbaceous cover less than about 12 inches (30 cm) high. Such surfaces that are likewise visible, but under taller shrubs and trees, count as exposed soil. Exposed rock that "burned" due to prefire covering of litter, duff or vegetation should be treated as newly exposed soil. The key interpretation is change in the percent cover. Ash and charcoal from consumed woody fuel, as well as newly exposed fine root mass within consumed duff layers, are overlooked when estimating exposed soil (that is, all the new soil below those components is considered). Change in soil color may also provide clues to severity. Base ratings on the proportion of exposed soil changing from native color to a general lightening with loss of organics at moderate to moderate-high severity, and up to 10 percent soil cover changing to a reddish color from oxidation at high severity. The amount of reddish soil varies by soil type, thus adaptation to particular ecosystems is warranted.

The following five examples are provided to help you sample the substrates:

1. If a plot had 20 percent exposed prefire rock (meaning no litter, duff, down woody fuels, or smaller herbs or shrubs covering the rock before fire), then only up to 80 percent of the plot could have burned. If fire consumed all litter, light fuels, and duff that covered the remaining 80 percent of the plot, then the estimated litter and duff consumption on the plot would be 100 percent resulting in ratings of 3.0 for both litter/light fuels and duff, and an entry of 80 percent for the percent of plot burned.

2. If 70 percent of a plot appears to be exposed rock or soil that existed before fire, you should not sample that plot in most cases.

3. A plot had essentially continuous cover of litter, light fuels, and duff before fire, and 80 percent of the plot burned (20 percent was unburned). If fire consumed all litter and light fuels and 50 percent of the duff within the area that burned, then plotwide litter and light fuel consumption would be 80 percent, and plotwide duff consumption would be 40 percent (half of the 80 percent of the plot that burned).

4. If fire consumed all litter and duff, and a fine layer of ash covers the soil, ignore the ash and treat the area as newly exposed mineral soil when rating that factor. You should scrape through the ash in places to examine the soil.

5. If a burn occurs in deciduous forest and it consumes all litter and duff before the current leaves have fallen, you should consider litter and duff consumption and newly exposed mineral soil to be 100 percent. Newly fallen leaves are not included in any of the substrate ratings.

Herbs, low shrubs and trees less than 3 ft (1m) rating factors

As with substrates, field personnel must determine initially whether herb, low shrub, and/or small tree rating factors are sufficiently represented on a plot to justify scoring them. The stratum should have been sufficiently present to indicate severity after fire. In general, suspected prefire coverage of less than about 5 percent of the plot, or limited distribution throughout might not be enough and may lead you not to count at least some of the factors. Such cases may occur under dense conifer canopies where the prefire understory consisted solely of needle-cast litter and duff, or in other cases, where vegetation was sparse and exposed soil was relatively high. At times, however, even small cover of herbs and low shrubs can be diagnostic, so take time before concluding not to score them.

Percent Foliage Altered—Percent of prefire woody-species cover that was impacted by fire as estimated by change in cover from green to brown or black. This only concerns the prefire low shrubs and small trees, not grasses and herbs. It includes girdle, scorch, and torch of needles, leaves, and stems. Resprouting from the base of shrubs or trees is not considered in this estimate of altered foliage, only the prefire foliage is. In other words, the entire blackened crown of a low shrub counts as prefire foliage altered, even though it may be resprouting. The amount of resprouting does not lessen the percent of prefire foliage altered. At high levels of severity, consumption of outer fine branching on low shrubs and small trees has occurred.

Frequency Percent Living—Percent of prefire vegetation that is still alive after fire. This is a measure of survivorship based on numbers of individuals and not necessarily on change in cover. Include unburned as well as burned, resprouting perennial herbs, low shrubs, and small trees plotwide. Resprouting plants are ones that burned but survive from living roots and stems. Include all green vegetation as well as burned plants that have not had enough time to resprout but remain viable. Burned plants may need to be examined for viable cambium or succulent buds near growth points. Dead stems will be brittle when bent; living ones will be supple. Do not include new colonizers or other plants newly germinating from seed. Make sure to take in the whole plot in the average score, including unburned areas.

New Colonizers—Potential dominance within 2 to 3 years postfire of plants newly generating from seed (native or exotic) averaged over the plot. The basis for this rating is the proliferation of such species due to fire, that is, above and beyond what might be expected had fire not occurred. Relative frequency of colonizers compared to established plants may be more recognizable at first, with relative cover increasing over time. This includes herbs such as like fireweed, thistle and pokeweed, as well as new tree or shrub seedlings. It also includes increased dominance of nonvascular plants that proliferate after fire in some areas, such as fungi, bryophytes, lycopodium, and small fine-leaved moss. Such plants should be rated with an understanding of how such species respond to fire. If you are not familiar enough with the species in a particular area to be confident in the appropriateness of rating these plant populations, then you should consult local botanists for assistance.

New colonizers also include aspen suckers that generate from former trees as well as similar tree-to-shrub responses from other species. Suckers are defined as stem growth originating from underground roots or rhizomes, as opposed to originating from branches or central trunks. All suckers are counted even though some may exceed 3 ft (1 m) in height, because 1) they represent a change in life form from top-killed trees; 2) they often disperse widely from spreading root masses; and 3) they are functionally equivalent to colonizers occupying new ground recently prepared by fire. Such effects are not counted in the tall shrub stratum, because 1) other colonizers in that stratum do not seem to exist, so the factor was omitted from that stratum; 2) it seems most efficient and representative to rate suckers within only one stratum and not two; 3) tree seedlings, which suckers functionally resemble, are counted only within the herb and low shrub stratum; and 4) no matter where they are counted, they will contribute the same to the understory CBI score.

For trees, include newly seed-established conifers, such as lodgepole pine, ponderosa pine, table mountain pine, long leaf pine, slash pine, or other coniferous or deciduous trees that colonize after fire. Tree seedling response after fire can be site specific, but in general, certain tree species are adapted to fire, taking advantage of fire-prepared soil and openings.

Species Composition and/or Relative Abundance—Change in species composition, and/or relative abundance of species anticipated within 2 to 3 years postfire. This is a community-based assessment that gauges the ecological resemblance of the postfire community compared to the community that existed before fire. It represents alterations in dominance among species (biomass or cover) as well as potential change in the species present, such as absence of prefire species and/or presence of new postfire species. Consider the distribution of abundance or dominance among the species present after fire, compared to before fire. Such factors qualitatively determine the similarity or dissimilarity of the site from before to after fire. Increases or decreases in certain species abundance and dominance, or changes in the species present after fire, raise the score for this rating factor.

These three examples are provided to help you sample the Herb, Low Shrub, and Trees less than 3 ft (1 m) tall.

1. A plot had understory cover distributed throughout all sections that seemed to consist only of perennial herbs. If 50 percent of the plot did not burn and fire appeared to have killed 90 percent of perennial herbs on the remaining 50 percent of the plot, then "frequency percent living" would be about 55 percent plotwide (50 percent unburned plus 5 percent resprouting). Foliage altered, on the other hand, would not be rated because the site did not appear to contain low shrubs or small trees before fire.

2. By observing nearby unburned areas, it was reasonable to assume that a burned plot still contained most, if not all, of the eight to 12 herb and low shrub species present before fire. It was also apparent, however, that a few small shrub species, such as *Vaccinium* and *Ribes,* were knocked back by the fire, while dominance of two herbs, *Calamagrostis* and *Epilobium,* was enhanced. Because original community composition was largely intact, and it was mainly just two species increasing with two decreasing, change in species composition/relative abundance could fall in a range of low to moderate on the CBI form. This would depend on the magnitude of change in dominance exhibited by the species diminished and enhanced by the fire.

3. If "frequency percent living" is low, and there are large numbers of new colonizers, then most likely change in species composition/relative abundance would be fairly high.

Tall shrub and trees 3 to 16 ft (1 to 5 m) rating factors

Percent Foliage Altered—Percent of prefire foliage for tall shrubs and trees 3 to 16 ft (1 to 3 m) that was impacted by fire as estimated by change in crown volume from green to brown or black. This includes girdle, scorch, and torch of needles, leaves, and stems. Resprouting from the base of shrubs or trees is not considered in this estimate of altered, only the prefire foliage is. In other words, the entire blackened top-killed crown of a tall shrub counts as prefire foliage altered, even though there may be a portion that is resprouting. The volume of the resprouting is ignored; it does not lessen the amount of prefire foliage altered. At high levels of severity, consumption of outer fine branching on shrubs and trees is evident. In fall burns and leaf-off conditions, base the score on effects to remaining boles and branches, the degree of outer branch consumption, and whether or not fire top-killed plants.

Frequency Percent Living—Percent of prefire tall shrubs and trees (3 to 16 ft) that are still alive after fire. This is a measure of survivorship based on numbers of individuals, not on change in cover or crown volume. Include unburned area as well as burned but resprouting tall shrubs and trees 3 to 16 ft (1 to 5 m) tall plotwide. Resprouting plants are ones that burned and survive from living roots and stems. Include all green plants, plus burned plants that have not had enough time to resprout but remain viable. Burned plants may need to be examined for viable cambium or succulent buds near growth points. Dead stems will be brittle when bent; living ones will be supple. Do not include new colonizers, such as aspen suckers or other plants newly germinating from seed. Account for potential mortality that could occur up to 2 years postfire (for example, conifer saplings that are 70 percent brown will likely die in 2 years), and make sure to average plotwide, including unburned areas.

Percent Change in Cover—Overall *decrease* in cover of shrubs and trees between 3 and 16 ft (1 and 5 m) tall, relative to the area occupied by those plants before fire. Count resprouting from plants that burned, plus the unburned plants, as cover that mitigates against or lessens the amount of decrease in cover. Do not include new colonizers or other plants newly germinating from seeds, including suckers that represent tree-to-shrub responses. Suckers from aspen and other species are counted as new colonizers that generate from underground roots or rhizomes, as opposed to coming from branches or central trunks. Make sure to average plotwide, including unburned areas. Account for potential mortality that could occur up to 2 years post fire. For example, conifer saplings that are 70 percent brown will likely die in 2 years.

Here is one example of how to score the Percent Change in Cover. A plot had 20 percent estimated cover for tall shrub before fire. An estimated half of that cover *did not* burn, and a tenth of prefire cover, though burned, was still green from resprouting. The remainder was burned and completely killed (no evidence of resprouting potential). The overall decrease in cover, would be estimated at 40 percent (100 percent minus 50 percent minus 10 percent), and given a factor rating of about 1.3. The prefire estimated cover of 20 percent would also be entered on the form.

Species Composition and/or Relative Abundance—Change in species composition, and/or relative abundance of species anticipated within 2 to 3 years postfire. Include prefire tall shrubs and trees 3 to 16 ft (1 to 5 m) tall as well as big and intermediate trees resprouting from the base. Basal sprouting from larger trees is included here because 1) the growth form changes from treelike to shrubby and then to multistemmed saplings; 2) basal large tree resprout does not seem to represent a fire effect that would be counted under tall-shrub/tree Frequency Percent Living; 3) growth tends to be restricted around root crowns and not spreading widely from the burned trunk, as in suckering; and 4) this needs to be counted somewhere, but only once, and these individuals will contribute to the large shrub/sapling community for some extended period of years. This is a community-wide assessment that gauges the ecological resemblance of the postfire community compared to the community that existed before fire. It represents alterations in dominance among species (biomass or cover), as well as potential change in the species present, such as absence of prefire species and/or presence of new postfire species. Consider the distribution of abundance or dominance among the species present after fire, compared to before fire. Such factors qualitatively determine the similarity or dissimilarity of the burned site to the prefire site. Increases or decreases in certain species abundance and dominance, or changes in the species present after fire raise the score for this rating factor.

Intermediate and big tree rating factors (combined)

Generally for northern and western conifer forests in the United States, the sum of the first three factors—Percent Unaltered, Percent Black, and Percent Brown—will be 100 percent. That may not be the case, however, in some deciduous forests or southeastern pine forests, where crowns may have been blackened or torched but not killed and subsequently resprout. In such cases, continue to score the unaltered, black and brown factors as they appear on the site, even though they may add up to more than 100 percent. The balance of the three factors should still maintain appropriate overall ratings for severity in the overstory.

Often insects or disease can affect fire-stressed trees soon after burning. If such effects are suspected and observed within a year or two of the fire, our tendency is to include them as fire-caused change. They would be relevant to the percent brown and canopy mortality rating factors below, as well as to supplemental factors, such as percent girdled and tree mortality.

Percent Unaltered (Green)—Percent of prefire crown foliage volume (living or dead) unaltered by fire, relative to estimated prefire crown volume of the plot. Include resprouting from burned crowns, but not from tree bases, as unaltered/green.

Percent Black (torch)—Percent black is prefire crown foliage (living or dead) that actually caught fire, stems and leaves included, relative to estimated prefire crown volume plotwide; may or may not be viable crown foliage after fire. At high severity, consumption of fine branching is evident. Do not consider resprouting from black branches as lessening the percent black. In many cases, deciduous trees will not torch especially when leaves are off; yet high flame lengths from the ground may blacken virtually the entire tree. Due to the aerial intensity of such fire and its similarity to crown fire, this type of burn is also included in the percent black rating.

Percent Brown (scorch)—Percent of tree canopy affected by scorch or killed by girdling, in relation to the estimated prefire crown volume over the whole plot. This is foliage killed by proximal heating without direct flame contact (such as brown foliage that did not actually catch fire). It includes scorching effects at the time of fire as well as delayed mortality, often from heat impacts around tree boles and roots. Suspected insect and disease effects also may be included, if that is manifested in the crowns relatively soon after fire (within about 2 years). This avoids a need to separate burn impacts from similar-appearing and related foliage conditions caused by fire-induced pathogens. Include crowns obviously impacted by these effects, even though brown foliage may have fallen to the ground. Include deciduous trees burned in leaf-off condition that are not resprouting from crowns. In those cases, look for dead crowns or portions of crowns that do not contain any black but may show severe charring around lower trunks or at ground level.

Percent Canopy Mortality—Of trees killed by fire or expected to die within 2 years, this should represent the proportion of crown volume now contributed by fire-killed trees (the proportion of once-living crown volume that is now dead). Consider in relation to crown volume still contributed by surviving trees. Only count trees that are completely dead, not the fire-killed portions of crowns that may still exist on living trees. One can count completely top-killed crowns on trees that show shrubby basal resprout. The factor is viewed as the proportion of a plot's total once-living canopy now lost because of recently dead trees. Suspected insect and disease effects also may be included, if that has contributed to killing whole trees relatively soon after fire (within about 2 years). This avoids a need to separate burn impacts from similar appearing and related foliage conditions caused by fire-induced insects or disease.

Char Height—The average height of char on tree trunks resulting from ground flames. This is the mean height on individual trees averaged over all trees in the plot. The mean height on a given tree is determined as halfway between upper char height and lower char height. Trees on slopes typically have char running up higher on the up-slope side, and wind-driven flames usually result in char running up higher on the leeward side of trees. Include unburned trees (char height = 0) and burned trees only where demarcation of ground char height is discernable. This rating does not include the black on upper boles resulting from crown fire. Trees that do not clearly show where ground flames ended and crown fire began are not included in the score. Thus, char height may not be applicable where crown fire predominates.

Three additional overstory factors are estimated but not averaged into CBI scores. These are entered as plotwide average conditions. They provide useful information to help interpret the rating factors for the overstory. Include recent postfire insect and disease effects where appropriate.

Percent Girdled (at root or lower bole)—Percent of trees effectively killed by heat through the lower bark, affecting the cambium around the circumference of lower boles or buttress roots. Girdling may or may not actually char through the bark and into the wood. It is often indicated a year or more after fire by sheets of bark loosely attached or sloughing off the lower bole. Include trees either dead or likely to die within 1 to 2 years. Do not include trees killed by crown fire or other scorching to crown.

Percent Felled (downed)—Percent of trees, whether dead or alive, that were standing before fire but now are lying on the ground. Such trees usually result from wind throw after fire. They typically exhibit fresh upturned root masses and charring patterns different from trees that were down when the fire occurred.

Percent Tree Mortality—Estimated percent of trees in each of the two size classes that died on the plot from the most recent fire or are expected to die within 1 to 2 years. The percent is based on the number of dead trees postfire compared to the estimated number of living trees before fire. Mortality should be judged on compelling evidence that, with 90 percent certainty, the trees are dead or will die.

Community Notes and Comments

Community notes or comments about burn patterns within the plot are optional but helpful in subsequent analysis. Attributes to consider here include 1) height and density of the various strata; 2) dominant species present per strata; 3) general fuel characteristics; 4) general microclimate, moisture, and topography; 5) evidence of insects or disease; and 6) any descriptors about the burn mosaic. Other comments may refer to the suitability of the plot, for example, when the plot straddles an edge or has signs of disturbance other than fire, such as postfire salvage logging or other rehab. Record any information that may potentially be useful to others, such as observations of rare plants, cultural resources exposed or affected by fire, interesting wildlife (including carcasses) as well as erosion or water quality evidence.

Data Sheets

The **BI Field Form** is for use in the field when direct digital entry is not possible. It includes the scaled criteria for rating severity factors, which helps calibrate field interpretations among observers. The **Cheat Sheets** and **Field Documentation**, in this chapter should also accompany field crews to aid in standardizing definitions of strata and rating factors. Once back in the office, recorded data can be entered using the FIREMON database software for PD (Plot Description) and BI (Burn Index), or the National Park Service FEAT database software. Note, strata mean scores and the CBI ratings will be computed on the fly as data are entered in BI or FEAT. Check these values against those calculated in the field, and correct the data sheets if necessary. At the time plot photos are digitized and given filenames, that information is entered in the FIREMON PD table. Entry of digital plot photo filenames can also be made on the appropriate data sheet.

REMOTE SENSING MEASURE OF SEVERITY: THE NORMALIZED BURN RATIO

If Unfamiliar With the Science of Remote Sensing

Many excellent references to general principles, methods, and applications of remote sensing can be found on the Internet. A recommended subject matter text is *Remote Sensing and Image Interpretation*, by T.M. Lillesand and R.W. Kiefer (1994). Most fires over 500 acres that occur on public lands are now routinely processed for perimeters and severity using the dNBR. Data are continually made available by USGS and USFS over the Internet; therefore, there is less cause for individual managers or scientists to produce these results, except perhaps under special circumstances or for research. Still, the discussion below serves to document the methodology, and provide the necessary background for both producers and users of results.

Introduction to the Normalized Burn Ratio (NBR)

Raw Landsat multispectral data contain a wealth of information about earth's features. Each spectral band responds in unique ways to surficial characteristics such as water content, vegetation structure, productivity, and mineral composition. When brightness values of multiple bands are combined in mathematical algorithms, information about targeted features can be enhanced, isolated, and analyzed. From available raw data, the challenge is to develop a specific index providing an optimum measure and useful signal for fire-effects, given the available bandwidths to work with. The index we developed is called the Normalized Burn Ratio (NBR). It is similar in construct to another standard index, called the Normalized Difference Vegetation Index (NDVI). The primary difference is that NBR integrates the two Landsat bands that respond most, but in opposite ways to burning (fig. LA-7). Those were determined to be TM/ETM+ Band 4 and Band 7. The NBR is calculated as follows:

Equation LA-1 $$NBR = (R4\text{-}R7)\ /\ (R4\text{+}R7)$$

where *R* values are the calculated per pixel "at satellite" reflectance quantities per band, which have been corrected for atmospheric transmittance.

Based on experience in generally forested ecosystems of the Western United States, *R4* decreases while *R7* increases from prefire to postfire TM/ETM+ acquisitions. The change is greatest in magnitude compared to other bands, and the variance within burns is greatest for *R7*. The combination of those traits appears to provide the best distinction between burned and unburned areas. It also provides an optimum signal, over other Landsat band combinations, for information about variation of burn severity found within the burn. The ***(R4-R7)*** difference is scaled by the sum of the two bands to normalize for overall brightness that is consistent across the bands. It helps remove within-scene topographic effects and between-scene solar illumination effects. This effectively isolates the real reflective differences between the bands, which enables spatial and multitemporal comparison of the derived NBR values.

To isolate burned from unburned areas and to provide a quantitative measure of change, the NBR dataset derived after burning is subtracted from the NBR dataset obtained from before burning, such that:

Equation LA-2 $$dNBR = NBR_{prefire} - NBR_{postfire}$$

This measured change in NBR, delta NBR, or dNBR, is hypothesized to be correlative in magnitude to the environmental change caused by fire (the burn severity as it relates to fire effects on previously existing vegetative communities). Assuming unburned terrain is relatively similar in phenology and moisture between the two sample dates, and the two datasets are adequately coregistered, background areas take on values near zero in dNBR. Likewise, burned areas assume strongly positive or negative values, depending on whether the fire distresses or actually enhances productivity on the site. The latter

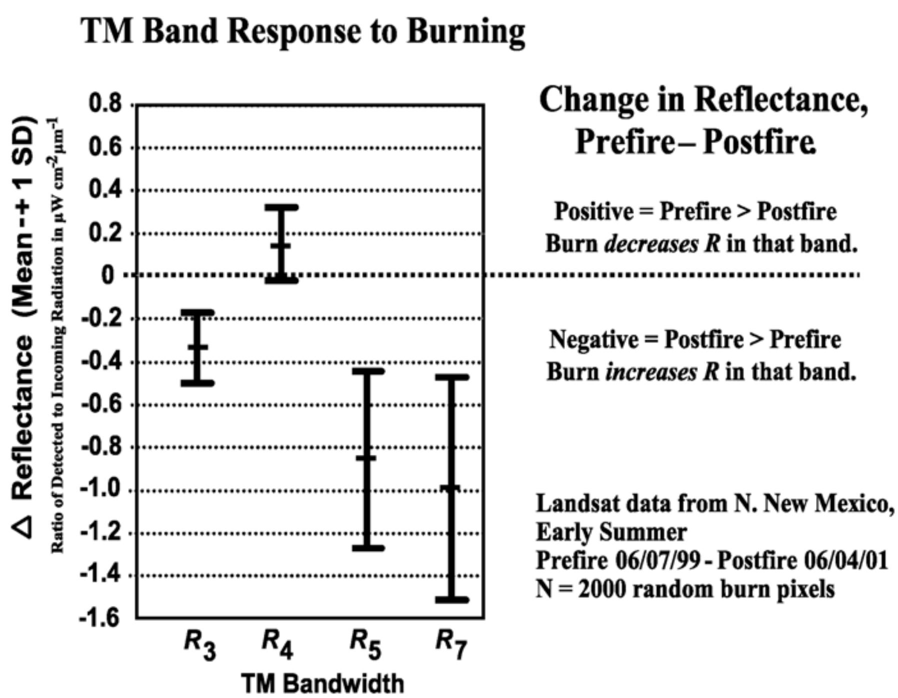

Figure LA-7—Change in band reflectance and the variation from before to after fire is indicative of each band's information content for severity. This example is typical for most burns. R4 shows the greatest decrease while R7 has the greatest increase after fire. Their difference yields the greatest range of change across all bandwidths.

can occur in herbaceous communities where severity is light and ephemeral, and burned vegetation responds quickly with renewed vigor from the release of nutrients or other factors after fire. Strongly positive dNBR is more typical, however, in forested and shrub-dominated areas where fire generally creates longer lasting conversions of biomass to less productive or earlier successional states.

In either case, burned areas can be suitably distinguished from unburned, and potential exists for a wide range of dNBR within the burn (depending on actual characteristics of the subject fire). This range appears to resolve the breadth of fire effects, revealing the complexity and spatial heterogeneity of the burn. It also appears to provide a broader range than other radiometric indices tested, such as the differenced NDVI. Results are constrained by the 30-meter Landsat resolution, however, which makes the index appropriate for landscape perspectives that yield whole-burn spatial data on severity.

Timing of Landsat Acquisitions

The dates from which pre- and postfire data are acquired by the TM/ETM+ are extremely important. If not carefully considered, they may be the primary pitfall leading to unsatisfactory results.

One contributing reason is that our approach involves change detection specifically targeting burned areas. Ideally, results show only change caused by fire, with all other surface features remaining neutral so as to elucidate the unburned areas that did not change. Unfortunately, unburned features in the landscape do not remain static over time, because they are naturally altered by wetting and drying, and cycles of productivity (fig. LA-8). As a result, the NBR difference, though apparently very good at resolving burn variations, still may be affected by such factors. (Other band combinations tested were influenced by seasonal acquisition timing to a greater degree than NBR.)

Therefore, to better isolate and enhance the burn signal, the pre- and postfire Landsat datasets should be chosen to represent moisture content and phenology as similarly as possible. This timing is relative to localized growing seasons, which may vary by date and location from year to year. Landsat scenes should be compared in false color for indications of seasonal differences (Bands 4, 5, 7 or 7, 4, 3 for red, green, blue, respectively). Two helpful characteristics to key on are 1) the productivity indicated by Band 4 in herbaceous and shrub communities, which typically shows strong seasonal patterns of regrowth, decline and curing out, and 2) the pattern of seasonal snowmelt or other regular change in surface moisture. Available Landsat scenes can be viewed on line to appraise these trends:

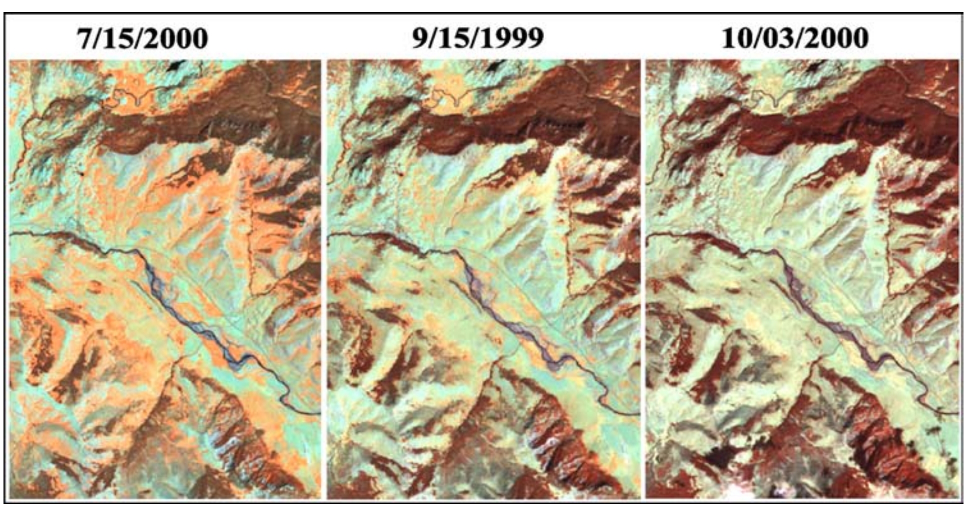

Figure LA-8—Seasonal difference in phenology is evident in false-color Landsat images from the Lamar Valley of Yellowstone National Park, Wyoming. The unburned landscape is not static as communities progress from productive (left) to unproductive states (right).

http://edcsns17.cr.usgs.gov/EarthExplorer/

http://edclxs2.cr.usgs.gov/

(See the links for ordering Landsat data provided in the **Recent Landsat Satellites** section of this chapter).

Of annual periods, early to middle growing season dates seem to yield best results. That is when unburned vegetation is green and lush (orange-red in fig. LA-8), showing peak contrast with areas affected by fire. Results remain good through late in the growing season, but as areas dry and deciduous plants cure (blue-gray in fig. LA-8), some resolution of the burn may be lost. In tests, NBR tended to minimize this issue, unlike NDVI, which degraded more strongly late in the season. Especially, distinction between unburned and low burn severity tends to diminish late in the growing season. By then, cured-out vegetation can mimic fire effects, and burn effects show less contrast against the background of unchanged but dry vegetation.

With these issues in mind, optimal timing of TM/ETM+ acquisitions may be difficult to achieve given cloudiness and the 16-day return interval of the satellite. If so, consider increasing options by reviewing even predominantly cloudy scenes. Cloud-free areas need only extend enough to encompass the burn(s). In addition for the prefire scene, data acquisition can safely occur within 2 or perhaps 3 years before the burn as long as other landscape disturbances (including interim fires) are accounted for and do not interfere with the subject burn. See discussion below for options on the postfire scene.

Two Strategies, Initial Versus Extended Assessment

With some exceptions, many severity indicators are apparent soon after fire is out. These have to do with scorching, charring, and consumption of living vegetation and dead fuel, and with changes in the nature of exposed mineral soil and ash. The exceptions, though, are important. They concern initial recovery of vegetation and delayed mortality, which also contribute to near-term severity. Often those factors may not become evident until at least the following growing season, so some passage of time may be required to get the fullest assessment of the burn. Given these circumstances, we recommend two scenarios for processing and applying dNBR severity measures (fig. LA-9).

Initial assessment

The Initial Assessment bears upon the most immediate fire effects to biophysical components that existed at the time of fire. It uses a postfire TM/ETM+ scene acquired when 1) the fire is as completely out as possible, and 2) when good remote sensing conditions exist. Note, these conditions cannot always be met for rapid response when rehabilitation plans need to be developed within about 2 weeks of significant burning. In order to match phenology (see discussion on Timing), the prefire scene generally

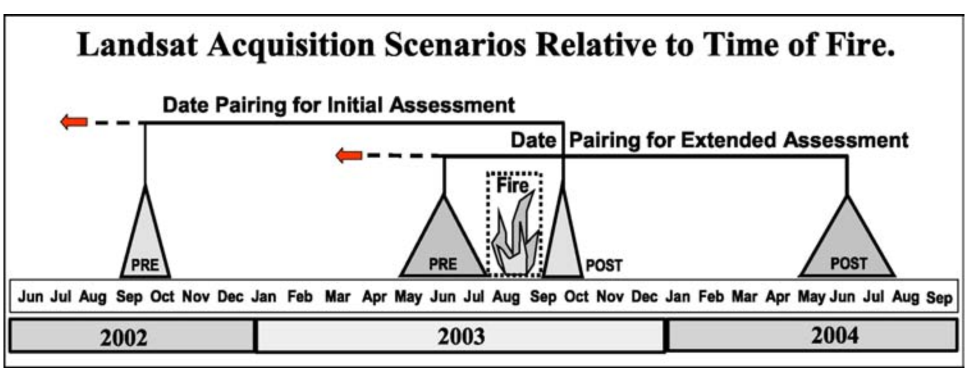

Figure LA-9—Initial and extended assessments require imagery from different periods before and after fire. The timing significantly affects what the NBR is measuring.

comes from a similar period of the previous year, or if necessary, the year before that. The only exception is if the fire was short-lived, and both scenes could be acquired within 8 to 24 days of one another. The latter also assumes there were no marked changes in moisture or productivity over the period. Initial assessment can provide good delineation of burned area and preliminary estimates of severity. It may not be optimum, though, for the following reasons: 1) vegetative regeneration will likely be missing, which may lead to overestimating severity; 2) unburned vegetation may be naturally cured out by the end of the fire season, diminishing burn contrast (see Timing); and 3) when the fire season extends from late summer into fall, sun angles may be low and there may be limited time before bad weather and/or snow obscures the burn. Late-season initial assessment, though perhaps the only timing available for some emergency response applications, may show less definition of the perimeter, less data range and contrast within the burn, and poorer correlation with field data. When possible however, severity will certainly be suggested because this timing integrates at least part of the suite of factors responding to fire. Importantly, we found that dNBR was less affected by late season effects than other indices, such as ΔNDVI, and concluded that dNBR held up better and was still useful in late-season. As such, initial assessment can yield figures on burn size, composition and complexity within a month or two of the fire. Products may suffice for many needs concerning public information, planning, and rehabilitation.

Extended assessment

The second scenario provides an extended assessment, which we believe is more representative of the actual severity. It postpones acquiring the postfire TM/ETM+ scene until the next growing season, which may be as soon as a few weeks or as long as 11 months after fire, depending on the ecosystem and climate. The prefire scene is then usually taken from that same seasonal period but during the year of the fire, since that period typically falls before a given fire season. If necessary, a prefire scene can come from a year or two before fire, so long as conditions are comparable and no interim disturbances overlap the burn. By waiting until the following season, burned vegetation has had a short time to recover and demonstrate additional responses indicative of initial severity. Delayed mortality may also be evident, revealing that plants green right after fire had died by the next growth period. Extended assessments would be most useful for final portrayal and summary of short-term severity or first-order fire effects. They would be suited for projects that depend on more accurate delineation of burn heterogeneity than initial assessment, like those comparing multiple burns over space and time, testing methods, or modeling. They also might better address long-term ecological consequences, such as impacts to sensitive communities or species, or risk factors like erosion and future fire potential.

Prefire Considerations

General software requirements

Several image processing systems can fulfill the needs of these procedures, such as ERDAS Imagine or GRASS, which analyze geographically referenced image data. Whatever system is used, there are two capabilities that, while not unusual, may be unavailable in some systems. First, one will have to be able to write and execute algorithms that incorporate raster datasets as variables, and output raster datasets as results. Second, one will need to be able to do mathematical operations in floating-point math, which requires manipulating and storing rasters in signed 16-bit or 32-bit data formats, that is, two or four bytes per pixel, because pixels can take on positive or negative values with at least four significant digits. The software also should be able to generate topographic slope and aspect data from a Digital Elevation Model (DEM). If not part of the image processing system, a statistics package is recommended to perform regression analysis for normalization of atmospheric effects.

General hardware requirements

Anticipate working with a large number of big data files in excess of 40 megabytes each. Steps can be taken to subset large scenes into smaller working regions, but some processes are best done on full scenes, especially if there is any possibility the data might be used for future fires or other applications.

Minimum starting disk space should be in the 10-gigabyte range; minimum RAM should be at least 256 megabytes. You will find a need to eventually manage around these limitations if work expands much beyond a couple of fire years in any one-scene area. A 21-inch graphics monitor is also recommended for on-screen interpretations and digitizing.

Digital geographic data needs

Besides two Landsat scenes (prefire and postfire), other types of thematic GIS data are highly useful for checking registration, orienteering, or supplementing maps. A digital elevation model (DEM) of the burn surroundings is recommended. DEMs are available at no cost from the EROS Data Center if "terrain" or "precision" corrected Landsat data are ordered. Those DEMs encompass the entire area of the scene, so the file is quite large. Some basic vector datasets for ownership, roads, trails, watersheds, lakes, and streams are also helpful, as well as digital raster graphics (DRG) and digital orthophotoquads (DOQ). Finally, there may be digitized fire perimeters from the fire incident teams that can help locate the general area of the burn. Keep in mind, these perimeters may not include all burned area and may vary in the quality of reference data available, even over the time of one fire.

Ordering the Data

Once the timing and assessment types have been decided, and the seasonal requirements for pre- and postfire Landsat datasets are understood (see above), search the Landsat archives for available scenes that best meet requirements. Both Landsat 7 and Landsat 5 data may be available, so both archives should be searched. You will need to obtain the chosen scene identifiers prior to ordering. These relate to the satellite path/row (or the geographic area covered) and the date. For more information on how to preview and order data, see the **Recent Landsat Satellites** section of this chapter.

When ordering the data, there are a number of format and processing options to choose from. For complete listings with definitions see:

http://edcdaac.usgs.gov/tutorial/daacdef.htm

For description of processing levels see:

http://landsat7.usgs.gov/l7_processlevels.html.

A sample specification is shown below for one Landsat 7 scene. Options in bold are recommended for all orders. The rest depend on your specific area, date, and working map base. If the datum is other than the default NAD83, it must be clearly specified. The highest standard processing level for ETM+ is L1G, which is geometrically corrected without ground control or relief models. We recommend, however, special-order level L1T, terrain corrected from ground control and relief models. It must be unambiguously specified, however, or processors will assume one of the lower levels. It costs extra, but it is well worth it, because terrain registrations are time consuming and may not be possible to do "in house." One additional option is to order the DEM for the scene area. This can be included at no cost, but will probably only be needed once per path/row, or not at all if a DEM is already available. As with Landsat data, map projection and datum should match what is in current use by the end user.

Item 001

Data granule: E1SC:L70RWRS.002:2001192063
Data set: LANDSAT-7 LEVEL-1 WRS-SCENE V002
Path/Row: 43/34
Acquisition Date: 02 July 2000
Ordering Option: E1SC:L70RWRS.002:2001192063:
L1T Product - **TERRAIN CORRECTED** UTM Projection
Cost: US $800.00
Format/Media: FASTL7A: CD-ROM: ISO 9660
Additional Information: WITH TERRAIN CORRECTION USING NAD27 DATUM

ORDER Options:
- Product: **L1T**
- Projection: UTM, ZONE 11, NAD27 DATUM
- Radiometric Correction Method: **CPF**
- Band Combination: **1; 2; 3; 4; 5; 6L; 6H; 7; 8**
- Image Orientation: **NUP**
- Resampling Method: **CC**
- Grid cell size for the pan band (8): **15.0**
- Grid cell size for the reflective bands (1-5, 7): **30.0**
- Grid cell size for the thermal bands (6L, 6H): **60.0**
- Zone Number: 11

These are the recommended options, given the following factors. Further processing involves reflectance-based calculations, so terrain registration is important. Multitemporal comparisons will be made, and pixel boundaries will shift scene to scene, so the resampling method should provide the best estimate of reflectance for the geographically rectified space.

Steps to Process NBR and dNBR

The steps outlined below are intended to be somewhat generic, recognizing that differences exist between various processing systems available to users. In general, steps identify what is needed along the way and not so much how to get there. One will need to find the proper procedures and syntax available within one's specific system. Systems usually provide analogous functions, so one should be able to adapt steps easily enough. We assume those undertaking these procedures are well grounded in remote sensing principles, and the functionality of the processing system in use. If not, one may want to consult a local expert.

I. Initial setup for operations for each Landsat scene:

1. Review the known facts about the burn, location, start and end dates, approximate size, and geographic distribution.
2. Plan a naming convention for the large number of files to be generated. A recommended sequence is provided in the **How-To** section of this chapter.
3. Extract the Landsat scene header file and print it out for reference.
4. Import Raw Bands 4 and 7 into image processing system (or GIS) for analysis.
5. Recommended, but optional, import other bands to explore data in false color.
6. Review the burn area displayed on the pre- and postfire imagery. Become familiar with its distribution within the surrounding landscape and juxtaposition to geographic features and named places.
7. Ensure compatible map projections exist between all data layers, and check registration of Landsat scenes, one to another and in conjunction with basic reference data (such as lake boundaries). Misregistration of more than one-half pixel should be corrected.

Note: Some image processors save rasters only as integer data, while the following calculations are done in floating point math and generate datasets of real numbers. If that is a problem, reflectance and subsequent NBR calculations can be scaled by 1,000 to retain positive or negative integer values with four significant digits.

II. Radiance and reflectance transformations: The procedure is used to derive "at satellite" reflectance for Band 4 and Band 7 of each Landsat scene. To expedite calculations, an executable script can be written and calculations can be combined in one algorithm. The script can then be modified for subsequent analyses by simply replacing the scene-specific parameters.

Note: these transformations are not specific to remote sensing of burns. Rather, they are recommended for any analysis that involves quantitative comparison of different Landsat scenes. They standardize the bands, account for drift in the multispectral scanner, normalize daily variation in sunlight, and optionally, correct illumination differences caused by topography. Standard order for processing mathematical operators is used.

The radiance per pixel per band is calculated as:

Equation LA-3 $$L_i = DN_i * G_b + B_b$$

where i is a particular pixel, DN_i is the per-pixel raw Landsat band brightness value (density number, or digital number), G_b is the gain and B_b is the bias for a particular band, b (in this case, Band 4 and Band 7). The G_b and B_b are reported per band in the scene header file.

The reflectance per pixel per band is calculated as:

Equation LA-4 $$R_i = (L_i * \pi * d^2) / (\mathrm{Esi}_b * \cos(z_s))$$

where d^2 is an eccentricity factor for Earth-to-Sun distance, Esi_b is the per-band exoatmospheric solar irradiance constant, and z_s is the per-scene Sun zenith angle. Here, the underlying assumption is that the Earth surface is flat, and only the sun zenith angle is used to calibrate Esi_b in the denominator. While topographic variables (pixel slope and aspect) have a bearing on surface reflectance, subsequent ratioing of NBR mathematically cancels those factors out, so it makes no difference whether those factors are included or not. Thus, in the case of calculating NBR, we use the simplified at-satellite reflectance algorithm. For more information on variable terms, refer to the **Glossary** section of this chapter; also, refer to the sections on **Reflectance Terms and Reflectance Incorporating Topography** in the **How-To** section of this chapter.

The reflectance algorithm yields values with a theoretical valid range of 0.0 to +1.0, or if scaled by 10^3, that is 0 to +1,000. They are a per-band ratio of detected surface brightness to the incoming solar radiation available at the top of the atmosphere, which allows the bands to be compared directly, as in the NBR.

Note: Landsat scenes acquired through the Multi-Resolution Land Characteristics Program (MRLC) from the USGS EROS Data Center may already be in reflectance units, and would not need the processing outlined above. Those data are rescaled to an 8-bit byte range of 0 to 255, however, and can be used without modification. The data will have a slight impact by reducing the spectral resolution of input bands, but the range and other statistical qualities of NBR will be approximately the same as using 16-bit or 32-bit data.

III. Transmittance normalization, for Band 4 and Band 7 of one Landsat scene: This addresses the fact that atmospheric clarity varies spatially and temporally, and the ability of light to penetrate the atmosphere (transmittance) varies per bandwidth as light is scattered by particulates and moisture. If one compares multiple dates of Landsat data, such effects should be minimized to avoid influences on surface reflectance. In some cases, multitemporal datasets are so similar in atmospheric clarity that this normalization is not necessary and may be skipped. Steps should still be taken, however, to first determine if that is the case. For those wishing more rational and detail on this method, see **Atmospheric Normalization** in the **How-To** section of this chapter.

Note: Atmospheric normalization is not currently done by the USGS EROS Data Center for scenes used in national programs, such as MRLC or the NPS-USGS National Burn Severity Mapping Project. This is due to a judgment that the effort would be too complex and costly for the improvement realized, given the large number of scenes involved in such national repeat coverage.

IV. Computing NBR for each Landsat scene, prefire, and postfire: At this point one has pre- and postfire reflectance datasets for TM/ETM+ Bands 4 and 7. If need be, one of the datasets has been transformed by regression to normalize for atmospheric effects. The calculation of pre- and postfire NBR is then straightforward:

Equation LA-5 $$NBR_s = (R4_s - R7_s) / (R4_s + R7_s)$$

Where, NBR_s is the per-pixel normalized burn ratio for scene *s*, and *R4* and *R7* are the calculated reflectance quantities, as described above, for the respective bands per scene. Note, the NBR has a theoretical range of –1.0 to +1.0, or if scaled by 10^3, –1,000 to +1,000 (fig. LA-10).

V. Computing dNBR from the pair of NBR datasets: The NBR difference is then computed:

Equation LA-6 $$dNBR = NBR_{prefire} - NBR_{postfire.}$$

This integrates multitemporal NBR datasets into a single gradient, or a one-dimensional scale. The difference measures change in NBR that occurred from time before fire to time after fire. The dNBR has a theoretical range of –2.0 to +2.0, or if scaled by 10^3, –2,000 to +2,000 (fig. LA-10).

NBR Responses

By understanding how individual TM/ETM + Bands respond, one can grasp relationships of the NBR to burn characteristics. The NBR incorporates Band 4 reflectance (*R4*), which naturally reacts positively to leaf area and plant productivity, and Band 7 reflectance (*R7*), which positively responds to drying and some nonvegetated surface characteristics. Band 7 has low reflectance (it is absorbed) over green vegetation and moist surfaces, including wet soil and snow—just the opposite from Band 4.

Because NBR measures the difference of *R4* minus *R7*, it is positive when *R4* is greater than *R7* (fig. LA-10). This is the case over most vegetated areas that are productive. When it is near zero, *R4* and *R7* are about equal, as occurs with clouds, nonproductive vegetation (cured grasses), and drier soils or rock. When NBR is negative, *R7* is greater than *R4*. This suggests severe water stress in plants and the nonvegetative traits created within burns. There one finds, for example, decreased vegetation density and vigor that *R4* responds negatively to, coupled with increased exposed substrates and charred fuels, which *R7* registers positively. Charring of living and inert components, drying, and soil exposure

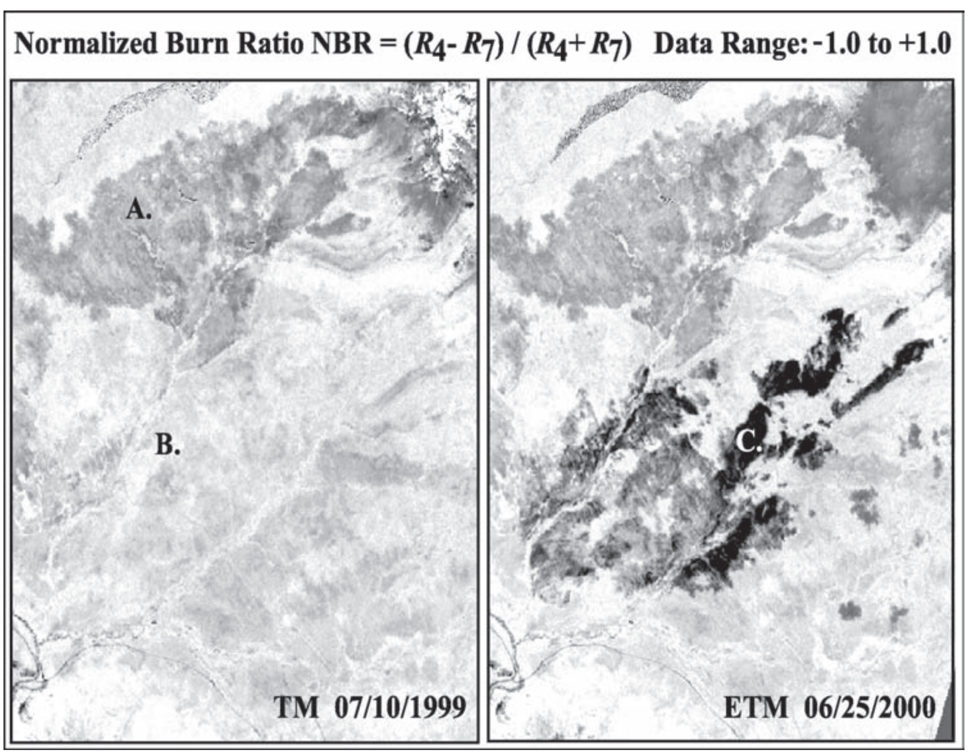

Figure LA-10—Pre- and postfire images of NBR illustrate A) values near zero from old burn; B) highly positive values of living vegetation; and C) strongly negative values of recent burn. Compare with figure LA-4 showing false-color composite images of this area.

enhance the signal registered by *R7* in comparison to *R4*. Results over recent burns, then, typically show near-zero to strongly negative NBR.

Interpreting Results of dNBR

Continuous data

Results are a model of severity. They measure the change that Landsat TM/ETM+ has been able to detect in NBR, a normalized difference of bands known to be highly sensitive to fire effects. The initial dNBR product is a continuous range of values that can be used directly for mapping and analysis (fig. LA-10). Assign a *linear* grayscale to the range of the data—one that provides good contrast—from unburned to highest burn conditions. We use a range of –800 to +1,100 dNBR that is assigned to the gray-level range of 0 to 255 (black to white). Unburned areas generally fall out as medium gray, and burns display a gradient of lighter grays with white at the high end. As hypothesized, the sequence of brightness corresponds to the gradient of severity.

Because they are a difference of normalized ratios, the units of dNBR are dimensionless. We tend to speak in terms of "points" that gauge magnitude of positive or negative change in NBR. From that we infer how strongly fire has affected a site. Individual values reference conditions averaged over the whole area of a pixel. Thus, a given value may represent either uniform distribution of one severity within the pixel, or small-scale patchy distribution of multiple levels of severity. Overall though, brightness for dNBR generally corresponds to a steady progression of effects relative to the prefire community:

1) Increasing char and consumption of downed fuels.
2) Increasing exposure of mineral soil and ash.
3) Change to lighter colored soil and ash.
4) Decreasing moisture content.
5) Increasing scorched-then-blackened vegetation.
6) Decreasing aboveground green biomass and vegetative cover.

Theoretically, dNBR (scaled by 1,000) can range between –2,000 and +2,000, but in reality it is rare for valid data to vary much beyond –550 to +1,350 (based on the scope of disturbance factors potentially affecting natural landscapes so far encountered).

Negative values result from postfire NBR being greater than prefire NBR. This may be due to clouds in the prefire image, or increased plant productivity in the postfire image. Enhanced vegetative regrowth is detected in approximately the -500 to -100 range of dNBR. A recent burn may exhibit this after one growing season if severity is light and the burn is in mostly herbaceous communities that recover quickly to exceed the productivity existing before fire. Also, older burns exhibit this as they recover vegetatively from the first year postfire into subsequent years. Pixels below about –550 are likely cloud effects, or noise caused by misregistration or anomalies in original Landsat data. Extreme negative (or positive) values also appear where data from one scene overlaps missing data in the other scene, as occurs near scene edges.

Ignoring the extremes, typical unburned signals fall approximately in the range near zero, –100 to +100. This indicates relatively little or no change over the time interval. Phenological differences between pre- and postfire scenes can shift the distribution of unburned values, sometimes as much as 50 to100 points.

Positive values occur when postfire NBR is less than prefire NBR (fig. LA-11). These may result from clouds in the post-fire scene, or from fire effects within a burn. The latter typically occupy a range between about +100 to +1,300. Values above about +1,350 are likely cloud effects. Cloud shadows do not have a pronounced affect on dNBR because NBR is a normalized ratio and is not influenced as much by brightness variation that is consistent across all bands—like that caused by shadow—as it is by inconsistent spectral differences between the bands. Cloud shadows, though, tend to boost dNBR slightly when in the prefire image, and decrease it slightly when in the postfire scene.

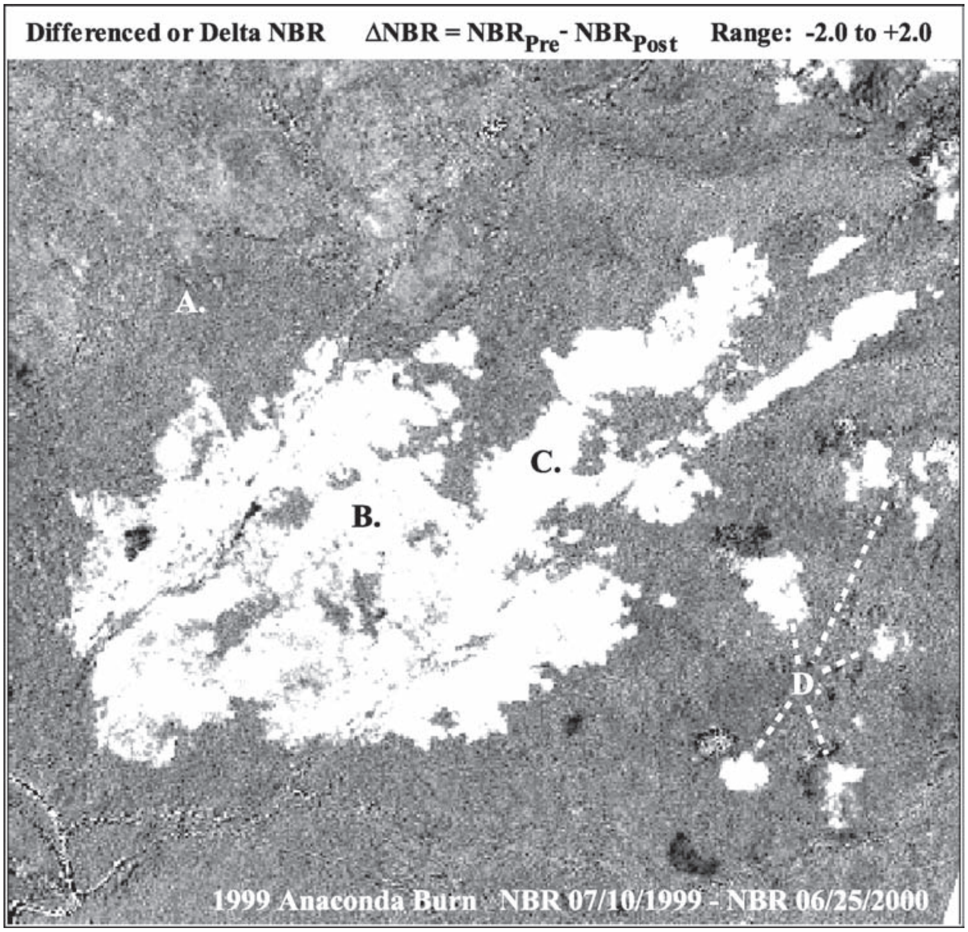

Figure LA-11—The difference of NBR images from figure LA-10 yields a gradient of detected change. A) medium-gray areas are near zero, indicating no change; B) lighter gray is moderate change; C) near-white is highly positive, indicating a large magnitude of change; D) is cloud in the postfire dataset.

Burn perimeter

One of the first things to do with the continuous data is to interpret the burn perimeter. Software may be available to automate this, but even so, those results should be reviewed, and then manually edited if necessary. If one does not have much knowledge of the burn, it is highly recommended to consult with others who do. Discrimination of burned area is enhanced when guided by direct field observation as much as possible. The objective of the perimeter, as we see it, is to delineate polygons that minimally encompass all burn areas. They can be used for graphic purposes, to calculate area statistics, or as a mask for isolating burn areas in GIS overlay processes (fig. LA-12). A manually digitized perimeter is quick and suitably accurate for 1:24,000 mapping. It provides a good way to plan sampling or to communicate information about burn size and distribution promptly. With a linear grayscale image of dNBR displayed on the computer monitor, digitize on screen following the boundary of the burned area. Zoom up to be able to faithfully follow the edge. You will need to decide on a level of generalization for the perimeter because the actual boundary can be quite complex and convoluted. The amount of detail is a matter of scale, limited by data resolution and intended use. It is also useful to have the pre- and postfire false-color composite images to refer to on screen.

As a rule of thumb, try to retain the obvious character of the shape of the burn when displayed at a scale where individual pixels are not so obvious. (For example, 1:24,000). Do not attempt so much detail as to be outlining each individual pixel. By and large, err on the liberal side; try to stay one-half to a whole

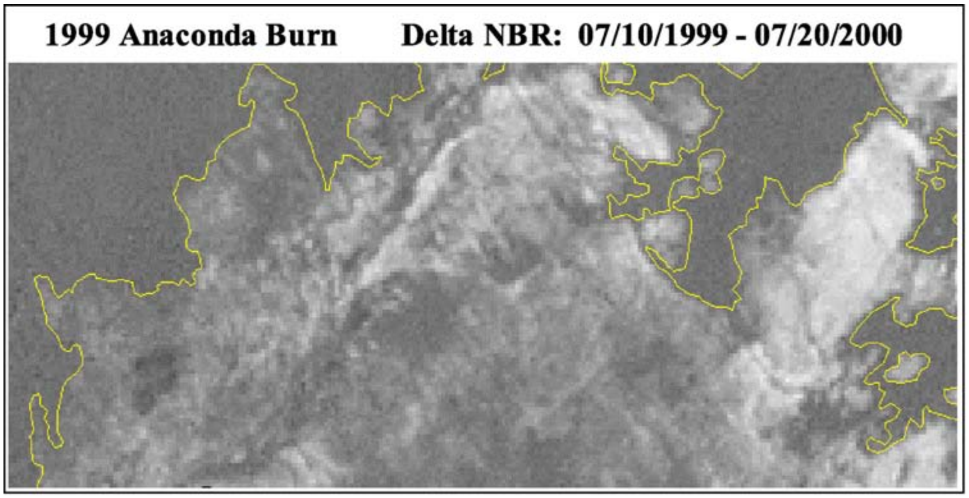

Figure LA-12—Enlargement of figure LA-11 showing detail of the digitized perimeter.

pixel outside the burn, and pass across small peninsulas of unburned areas that project into the burn, if less than about 3 pixels wide. Also, do not digitize around interior unburned islands, unless some specific objective requires it. In all these cases, the burned and unburned pixels included within the digitized perimeter should eventually be adequately identified by their dNBR values (for example, when it comes time for statistical summaries of the burn). Continue digitizing all disjunct patches of the burn created by spot fires, and label all polygons with a unique identifier.

Subsequent Procedures—Using the digitized perimeters, one can extract a histogram of all dNBR pixel values occurring within the burn(s). This is a basic reference for comparison to other burns (fig. LA-13). It supplies information on mean and variance of severity, and the frequency (or area) of values

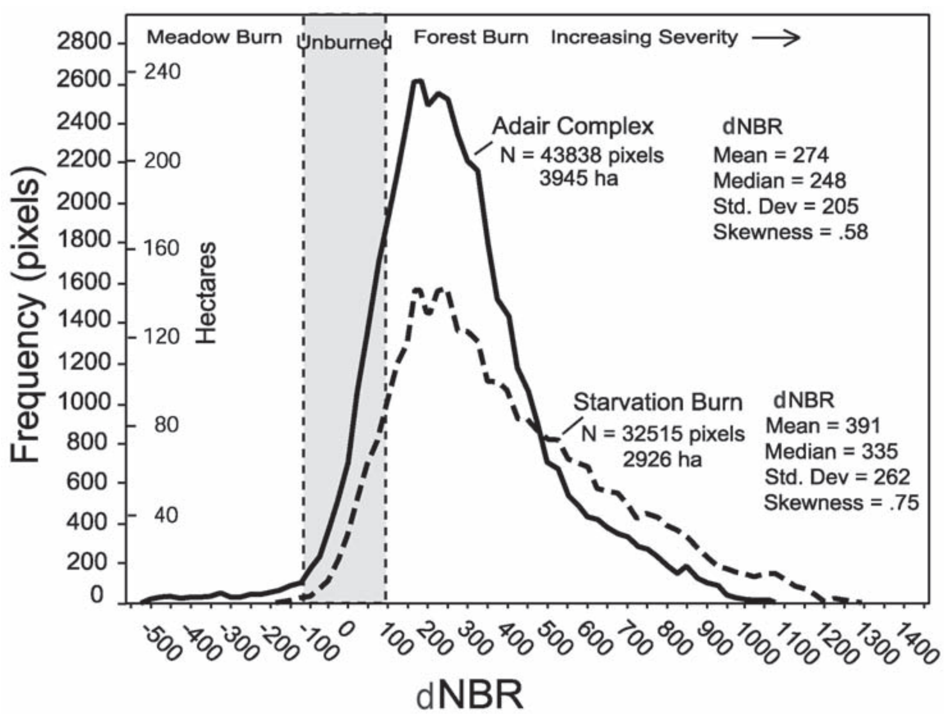

Figure LA-13—Frequency distribution of pixel values within two burns from1994 in Glacier National Park, Montana. Starvation had proportionately more area burned at higher severity than Adair.

occurring across the dNBR gradient. Histograms also may be used to break down the composition and aerial extent of burned patches, such as watersheds or forest stands.

Next, you will be able to identify target areas for field sampling with the perimeter, trails, roads, and other references (lakes and streams) overlaid on the grayscale dNBR. This allows you to find accessible areas large enough to represent the range of variability within the burn, as described in **Ground Measure of Fire Severity: The Composite Burn Index** section in this chapter.

Once field plots are located and sampled, plot locations can be mapped onto the continuous dNBR dataset using GIS overlay functions, and the pixel values from those locations extracted. There are many creative ways of doing this, including multipoint averages or weighted averages within a local neighborhood of the plot. Due to burn heterogeneity and improved GPS locational accuracy, we looked for alternatives to the commonly used 3 x 3 pixel average. We found that a straight average of 9 pixels too often interjects values in the average that are greatly dissimilar, and not representative of the plot. One option is to weight the center pixel by two or three times, and throw out one pixel that has the most different value from the center pixel. Instead, however, we tend to use a five-point pixel average, where the points for sampling dNBR are the plot center, and theoretically plus or minus 50 ft (15 m) from plot center. This results in 1 to 4 pixels being sampled per plot, depending on the juxtaposition of the plot center to the pixel center. The center pixel—the one containing the plot center—is always counted at least twice, providing extra weight to the center pixel in the average. If the plot lays dead center within a pixel, then this five-point sampling yields the value of only that 1 pixel.

The dNBR values extracted for all plots can then be imported into a database that contains corresponding plot CBI ratings, or other measures of severity determined in the field. At that time, analysis of the association between dNBR and observed severity can be undertaken. Field work may also detect where revisions to the perimeter are needed. Each subsequent step adds a level of verification that should be specified in the metadata.

Discrete ordinal data

Continuous dNBR datasets can be stratified into ordinal classes or severity levels to simplify description and comparison of burns (fig. LA-14).

The breadth and number of levels is entirely up to the user, based on requirements of the application. However, we commonly employ a seven-tiered configuration proven useful in a variety of ways (table LA-2). Value ranges of dNBR may vary between paired scenes. Values less than about –550, or greater than about +1,350 may also occur. If they do, they are not considered burned. Rather, they are masked out as anomalies caused by misregistration, clouds, or other factors not related to real land cover differences.

The first two severity levels (table LA-2) reflect areas where productivity increased after burning. They occur almost exclusively in herb communities where dNBR can be strongly negative from enhanced productivity after fire (the postfire NBR is much greater than the prefire). Typical unburned pixels occupy the range near zero. The last four levels include all other burned areas where dNBR is distinctly positive (the postfire NBR is much less than the prefire). They cover what is normally recognized as recently burned, including forest, shrub, and some herb communities.

Ordinal or nominal classes such as these are useful for a wide array of purposes like reporting aerial statistics, aggregating the statistics of many burns, stratifying for study of ecological consequences or treatment, quantifying burn heterogeneity, and mapping. Ordinal or nominal classes, however, can be quite variable case to case, depending on each project’s objectives and individual perceptions of burn severity.

Severity thresholds

Unfortunately, the threshold levels reported above are not hard and fast for all dNBR scenarios; they are somewhat flexible. Recent experience shows shifts for some burns in the range of about $\pm$ 10 to 100 points for a given severity level. At this time, we believe the primary causes for this variation are

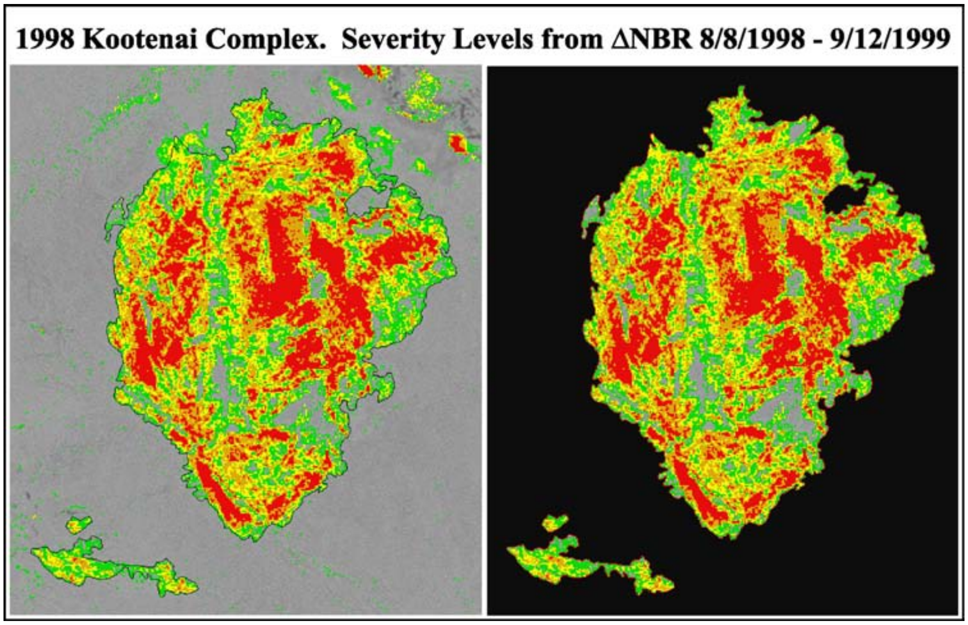

Figure LA-14—Stratified delta NBR image (left) and the data masked by the burn perimeter (right). Severity levels were derived from thresholds in table LA-2, showing unburned, low, moderate-low, moderate-high, and high as gray, green, yellow, orange, and red, respectively. Areas outside perimeter with elevated values are relatively easy to discern as snow, clouds, or dry patches away from the burn; refer to figure LA-2.

Table LA-2—Ordinal severity levels and example range of dNBR (scaled by 10^3), to the right.

Severity level	dNBR range
Enhanced regrowth, high	–500 to –251
Enhanced regrowth, lo	–250 to –101
Unburned	–100 to +99
Low severity	+100 to +269
Moderate-low severity	+270 to +439
Moderate-high severity	+440 to +659
High severity	+660 to +1300

(dNBR value ranges are flexible; scene-pair dependent; shifts in thresholds $\pm$100 points are possible. dNBR less than about –550, or greater than about +1,350 may also occur, but are *not* considered burned. Rather, they likely are anomalies caused by misregistration, clouds, or other factors not related to real land cover differences.)

1) seasonality of the images, and 2) whether the timing is for initial assessment or extended assessment. Under extended assessment, thresholds tend to elevate for early-to-middle season dNBR as that assessment exhibits greater range overall compared to late-season extended assessment. On the other hand, initial assessment may indicate considerably higher severity—requiring higher thresholds—when the postfire scene comes soon after burning, as opposed to the following growing season. When the postfire scene is drier overall than the prefire scene, the burn-unburned threshold tends to elevate somewhat, and there is a greater chance of confusion between the driest unburned pixels and lowest severity burned pixels.

If image timing is indeed a controlling factor—relative to time since fire and time of year—then scenario-specific scales for severity may be possible to achieve in the future. In the mean time, fine calibration of thresholds can only be done individually for each dNBR model using a combination of expert knowledge and correlation to ground data. We intend to add further guidance along these lines as the number of burns analyzed in different ecosystems expands.

Before ground data are analyzed, one can interactively color up ranges of the continuous dNBR data to determine preliminary severity level thresholds by computer (fig. LA-13). We strongly advise that this procedure be done by, or in consultation with, someone who has direct knowledge of at least portions of the burn on the ground. That will greatly facilitate and improve the initial classification of severity levels by introducing an ability to recognize spatial patterns as they were observed in the field.

Display the dNBR linear grayscale, and from the low end at about –100, progressively "color up" increasing values with one color. You will find the distribution of colored pixels being randomly scattered at first around the burn, then incrementally becoming gradually more localized, until mainly pixels near the edge of the burn are being colored. When the burn area is clearly delimited, yet not excessively to crop out potentially low severity pixels, the end value marks the approximate upper limit of unburned in terms of dNBR. The same procedure should be done in reverse, from the top down, to find the bottom threshold of low severity level. Then compare the burned-unburned endpoints, and revise the threshold as needed.

Do not be alarmed if some spurious "low severity" pixels show up well outside the perimeter where it did not appear to burn. That is to be expected when setting discrete boundaries for categories based on continuous data. On the other hand, you want to reach a threshold where those spurious pixels are at minimum, and at the same time have a "burned" pixel distribution that most faithfully defines the actual burn area. The quality of severity-level discrimination can be determined later statistically, when final judgments about reliability can be weighed with field data. At this time, however, some idea of how well dNBR is working can be inferred by examining how well the burn-unburned threshold either includes or excludes the burn, based on the distribution of seemingly errant pixels relative to correct ones.

Most errant pixels should be scattered randomly and relatively few in number. If there are some well-defined patches of pixels that seem to be wrong, the most likely cause is difference in moisture or phenology between the two Landsat scenes. For example, unburned meadow patches may be lighter than surroundings if the postfire scene is particularly drier than the prefire. In a case study of Yellowstone National Park burns at elevations above 6,000 ft, where early September and mid-October NBR values were differenced, the October scene was notably drier. Deciduous plants had become dormant in meadows and along riparian corridors, and those appeared faintly with elevated dNBR (fig. LA-7). If location of the burn is generally known, these cases should not be cause for concern. However, thresholds may need to be shifted up or down, depending on relative scene conditions indicated by unburned background.

Note there is always overlap in dNBR values between severity levels. To explore statistical properties of a particular dNBR, sample the population of unburned pixels. Large samples of unburned pixels (5,000 or more) typically display normal distributions with a mean of ±50 and a standard deviation less than 50. Include only areas that are not affected by extreme phenological or atmospheric differences, such as where a meadow was green in one scene and completely brown in the other, or where there was snow in only one scene. If such differences predominate over the unburned area, then the scene pair is probably not appropriate to use in the first place. The sample mean should indicate the bias from zero dNBR, which marks the theoretical value for no detectable change. If the unburned mean is shifted from zero, that indicates some nonfire related difference between the scenes, and the whole dNBR histogram could be shifted by that amount to standardize multiple dNBR scenarios (shifts up to ± 50 points can occur). Furthermore, two standard deviations should mark an approximate 95 percent confidence interval for the unburned class. From our experience, a standard deviation of about 50 points or less indicates a good pairing of the NBR scenes, with little nonfire related difference between them.

Next, it is useful to establish a lower threshold for high severity. Change to a different color and start at the high end of dNBR to progressively color in values decreasing from the highest. You will notice a point (value) where the first few pixels within the burn take on the color. This is the upper realistic limit of dNBR for that burn. If the burn is one that seems to include some extreme high severity, that value should be within a range of about +1,000 to +1,300. If that value is lower, it may be that severity did not reach maximum levels within the burn. If it is below about +600, it is possible that only moderately high levels were reached, and the burn contains no high severity. If it is above about +1,300, bear in mind it may result from clouds in the postfire scene or some other data anomaly. Examine the raw Landsat scenes to confirm that high values are not where clouds interfere with dNBR in the burn.

From that highest realistic value, continue coloring values incrementally down the scale. You will notice colored pixels appearing in a number of new locations, and then progressively fewer new locations. You will see increased clumping of newly colored pixels around previously colored patches, gradually appearing to fill out and expand existing patches. Isolated uncolored pixels within colored patches may indicate that you are missing some high severity, and the threshold should go lower still. At some point after patches are well formed, but before most of these patches coalesce and before lone pixels start to frequently show up in dispersed new areas of the burn, note the dNBR value. If it is within a range of about +600 to +750, you can assume you are within the range of a preliminary lower threshold for high severity. Based on knowledge of the burn—aerial photos or some other source—you may want to go further down or back up the scale to try to settle on the most reasonable breakpoint. This may be influenced in part by the size of the area identified as high severity. Remember that there may be a tendency for initial assessments to have higher thresholds for high severity, depending on the ecosystem.

If there are a few isolated pixels that are not colored within larger surrounding patches of "high severity," that may indicate the threshold for high severity is too high and needs to be lowered. In fire ecology terms, one might question the validity of a few isolated pixels remaining within large patches of high severity. Query the values of those pixels to determine if they should be included with high severity, as would be likely if those values are only a few points below the current high threshold. If they are quite a bit lower than the current high threshold, then those truly may be isolated areas of a lower level severity class. In the end, one should see a distribution of high severity that is not excessively fragmented or "speckled," while at the same time, not too broadly contiguous over an unreasonably large portion of the burn.

Apply the range between unburned and high severity just determined to partition the remaining positive severity levels. Refer to table LA-2 for proportions of those levels relative to a comparative span of about 560 points between unburned and high severity. If reliable information on the burn is available, the levels can be adjusted to fit what is known. For example, one may know that certain areas burned with low severity, so thresholds can be adjusted accordingly to correctly identify those areas.

The Enhanced Regrowth levels (strongly negative values) can be determined much as described above by reversing the progression of coloring the negative values. Start by going down from unburned into the Enhanced Regrowth Low level. Focus on areas within the burn where dNBR appears darker than the unburned medium-gray levels outside the burn. These should correspond to meadow or grassland habitats, if present. It helps to key on the distribution and shape of familiar meadow patches evident in false-color images or aerial photographs. The range of valid negative values is basically divided by one-third and two-thirds to split out low and high enhanced levels, respectively, assuming the total is a span of about 420 points or more. If much less than that, retain a span of about 100 points for the Enhanced Regrowth, Low level.

Subsequent procedures—The initial stratification of the burn can be analyzed for preliminary assessments, or taken into the field where adjustments to the model thresholds may become evident. Walk- or drive-through surveys are recommended with severity maps in hand to initially spot check for obvious agreements or discrepancies. More in-depth field work is usually required for statistical validation and calibration, and the map of burn levels is useful for locating target sample areas. Refer to the **Ground Measure of Fire Severity: The Composite Burn Index** section in this chapter for discussion of field protocols. The dNBR thresholds can then be revised as soon as consistent field observations are made. Once sufficient ground data have been analyzed, that should ultimately guide where thresholds most appropriately fall, based on statistically determined intervals.

Recognizing that ground data may never be available on some burns, thresholds for severity levels (classes) may need to be based on field results from other burns within similar ecotypes and similar timing of dNBR. After a number of burns have been sampled in a region, statistical confidence in thresholds for dNBR should increase to a point where subsequent ground data are less essential. At that time, plots can be sampled less frequently and used mainly to spot check results. That is, in fact, one goal of the whole process, so field time and expense can be minimized, without impacting availability and reliability of burn information.

Each subsequent procedure adds a level of validation that should be documented in the metadata. Once results are improved and verified as much as possible, the burn severity model can be used to compile final reports and statistics and to address a variety of issues.

LANDSCAPE ASSESSMENT HOW TO

How To Record a GPS Location

Basically, there are a number of options today for GPS receivers and ways to acquire locational data. Here are recommend protocols on only a few issues.

Acceptable accuracy

The two-dimensional accuracy of X (Easting), Y (Northing) coordinates reported by the GPS should be less than 33 ft (10 m), preferably less than 23 ft (7 m). There is no procedural requirement on elevation, or the Z coordinate.

Geodetic datum

The more accurate and more recent NAD83 should be selected, unless there is a strong need to use the data predominantly within a local GIS and the local standard is for some other datum. For example, many National Park Service sites still use NAD27 in order to reference data taken from their older base maps. These were some of the first areas mapped with USGS 1:24,000 quadrangles. In any event, it is important to note the datum used for plot location so conversions can be made if necessary.

When digitizing a single point

Y-Code receivers such as Rockwell’s PLGR, should be set to an averaging mode and allowed to log a number of points until the coordinates stabilize, at which time the plot center is either jotted down or saved in memory. These receivers are only available to approved Federal government employees.

P-Code receivers such as Trimble’s Pathfinder and GeoExplorer, or various Garmin models should be treated similarly only if “selective availability” is off. If “selective availability” is on, a differential correction should be used. Set the receiver to log and save a 100 or so points for each plot center. Options are to do differential correction “on the fly,” or later by receiving suitable reference control data from a surveyed base station. You will have to check with GPS-knowledgeable people in your area to learn how to access local base station data.

How To Take Plot Photos

It is a good idea to take photos *after* completing the rating exercise, when one is most familiar with plot burn conditions. There are many approaches to this, but some recommended procedures include the following. Use a high-resolution digital camera, or a 35 mm camera with color slide film, ASA of about 125. Take at least two photos approximately 180 degrees opposite one another, showing the plot center and about half of the plot in each. Avoid taking photos directly toward the Sun. Include a signboard for scale and to identify the date and plot number in the picture. As time or objectives allow, take any number of photos targeting features of interest; for example, typical charring patterns on substrates or trees, and regrowth of perennial herbs and shrubs. Try to capture tree canopy effects as well as ground effects.

How To Name Files for Burn Remote Sensing

Generally, it is beneficial to keep filenames as concise as possible and be consistent from analysis to analysis. Filenames can get quite involved, but try to include some indication of data content and level of processing, to simplify retracing steps and file lineage. These data are a time series, so it is helpful to use names that sort into a date sequence. Here are some suggestions:

YYDDD.bB—Raw Landsat bands can be named by date and band number, most simply with a two-digit year (four digits if necessary), three-digit Julian day (two-digit month and two-digit day, if necessary), "b" for Band, and the Band number, B.

Example: 01179.b4 designates Band 4 of a scene from 2001 Julian day 179, or 28 June.

Scenes of the same path have the same date sequence, so if scenes of the same path and date are kept separate and not seamlessly patched together (as could be), names may become ambiguous when used in the same analysis. In that case, a designator for row number can be added. Scenes of the same path that will always be used in separate analyses (such as one from California and one from Montana) are not a problem. They can be separated within directories of the file system. Landsat TM and ETM+ data will never be acquired from the same path/row on the same date, so redundancies should not occur between the two satellites. If it is found useful to distinguish them, a prefix of "t" or "e" may be used (for example, t01171.b4 and e01179.b4).

YYDDD.rB and YYDDD.trB—Band reflectance and transmittance-corrected reflectance data can use the same designation above, with substitution of "r" or "tr" in the extension.

Example: 01179.r4, 01179.tr4

YYDDD.n or nYYDDD—The normalized burn ratio for scene YYDDD carries the same form as above but with an "n" as an extension or as a prefix.

dYYDDDYYDDD.n or dnYYDDDYYDDD—The name identifies the operation ("d" for delta or difference), the two scene dates, and the index used in the difference ("n" for NBR). Differencing presents many possible scene combinations, so it helps to keep scenes explicitly identified in the name.

Example: d0018201179.n = NBR difference between 1 July 2000 and 28 June 2001—Julian days 182 and 179, respectively.

Variations might include different indices such as "v" or "vi" for the NDVI, or subsets of scenes that may require added codes for individual burns. A classification or rescaling of continuous data might add a "c" or "r" to the extension, such as dnYYDDDYYDDD.c to represent a file containing the ordinal severity classes derived from the delta NBR.

How To Handle Reflectance

This section is additional comment on the reflectance algorithm described in the **Steps to Process NBR and dNBR** section of this chapter.

Equation LA-7 $$L_i = DN_i * G_b + B_b$$

The radiance term (L_i) would be straight forward, except for the fact that gains and biases (G_b and B_b) have been reported differently over time, depending on the satellite generation, postprocessing software, and the vendor.

It is important to read the technical documentation accompanying the data to understand what units are being used and whether maximum and minimum radiance is being reported instead of true gain and bias. Generally TM data from EOSAT/Space Imaging Corp., a private corporation, are processed in "Fast Format," and reports gain and bias in milliwatts per square centimeter per steradian per micrometer. For a period, though, those values were actually maximum and minimum radiance, so a conversion is required to generate appropriate G_b and B_b. Recent procurement of TM and ETM+ data from the USGS EROS Data Center, on the other hand, will most likely be processed with NLAPS or L7 software, which generates gain and bias in watts per square meter per steradian per micron (a micron is equivalent to 1 micrometer).

Equation LA-8 $$R_i = (L_i * \pi * d^2) / (\mathrm{Esi}_b * \cos(z_s))$$

In the reflectance term (R_i), the exoatmospheric solar irradiance, Esi_b is the mean irradiance striking the uppermost atmosphere per-bandwidth, b. It is important for Esi_b to be in the same units as the gain and bias used to calculate radiance. The Esi_b also differs slightly between Landsat satellites, as the bandwidths are slightly different. Generally, for Landsat 5 TM data processed by EOSAT/Space Imaging Corp., Esi_b would be applied in milliwatts per square centimeter per micrometer:

Band:	1	2	3	4	5	7
L5, TM Esi_b :	195.7	182.9	155.7	104.7	21.93	7.452

For TM and ETM+ processed by the USGS EROS Data Center, Esi_b values are reported in watts per square meter per micron (a micron is equivalent to a micrometer):

Band:	1	2	3	4	5	7
L5, TM Esi_b :	1957.	1829.	1557.	1047.	219.3	74.52
L7, ETM+ Esi_b :	1970.	1843.	1555.	1047.	227.1	80.53

Note: Watts per square meter per micron is a factor of 10 greater than milliwatts per square centimeter per micron.

The Esi_b decreases steadily as wavelength increases to the right. For example, only about 1/13th the amount of incoming irradiance occurs in Band 7 as in Band 4. Thus, it would be difficult to associate the two bands directly, because Band 7 is naturally so much darker by comparison. The ratio calculated by reflectance, though, normalizes for this initial difference in irradiance magnitude. It produces a value between 0.0 and 1.0, which is then comparable between the bands. Reflectance is functionally equivalent to a simple percentage calculation, associating the amount of detected light with the total available.

The factor, d^2, makes minor adjustment in exoatmospheric solar irradiance, Esi_b, due to orbital eccentricity, or the daily deviation from average distance between Earth and the Sun (see the **Glossary** in this chapter). The d^2 ranges between 0.9666 and 1.0350, and it is closest to 1.0 in early October and early April. For a given day, it can be obtained from a look-up table. Refer to a reference dealing with solar radiation (for example, Muhammad Iqbal, *An introduction to solar radiation*).

In its most basic form, if one discounts surface topography and Sun angles, "at satellite" reflectance boils down to a simple ratio of radiance (or detected brightness) over the amount of available incoming solar radiation per bandwidth; in other words:

Equation LA-9 $$R_i = (L_i * \pi * d^2) / \mathrm{Esi}_b$$

All other factors in the algorithm simply modify Esi_b in ways to more realistically gauge the amount of incoming radiant energy that has potential for reflection off the Earth's surface. That, of course, initially involves the angle of the Sun in relation to zenith, as is the case assuming a flat surface:

Equation LA-10 $$R_i = (L_i * \pi * d^2) / \mathrm{Esi}_b * \cos(z_s)$$

This denominator simplifies the influence of incidence angles on Esi_b, where only the Sun zenith angle of a particular scene, z_s, is applied (see the **Glossary** in this chapter). When the Sun is directly overhead, $z_s = 0$ degrees and $\cos(z_s) = 1$, so the entire quantity of Esi_b is available for detection. As the Sun angle moves away from zenith, $\cos(z_s)$ decreases, serving to decrease the amount of available light (Esi_b) for detection. In a more complex formbelow, the algorithm incorporates topographic angles, which more accurately model the amount of incoming light hitting a pixel's surface. That, however, is deemed unnecessary for NBR analyses, as NBR per-pixel normalization cancels those factors, so use of either reflectance algorithm is mathematically equivalent.

Reflectance incorporating topography

The following is provided only for added understanding of reflectance, but is not required to complete the analysis of burns using the NBR. Such an approach may be preferred in other cases when normalized band ratios are *not* used, and comparisons between scenes depend directly on calculated per-band reflectance. The more complete rendering of reflectance has Sun direction and topographic factors built into the derivation:

Equation LA-11 $R_i = (L_i * \pi * d^2) / (\mathrm{Esi}_b * (\cos(z_s) * \cos(slope_i) + \sin(z_s) * \sin(slope_i) * \cos(a_s - aspect_i)))$

where, a_s is the per-scene Sun azimuth angle, and $slope_i$ and $aspect_i$ are the per-pixel topographic variables derived from a DEM. Note that aspect in degrees from north has "flat" reassigned to equal the Sun azimuth angle; such that, $a_s - aspect_i = 0$ for flat pixels.

When a DEM is available, the added terms in the denominator adjust z_s to approximately the actual incidence angles created by interplay of sunlight on topography. Generally, the terms increase available light as slope angles increase and aspects face toward the Sun. Conversely, reflective light potential decreases as slopes steepen and aspects face away from the Sun. On a flat surface, the topographic terms reduce to 1.0; so again, Esi_b is only modified by $\cos(z_s)$.

Because Esi_b and terms associated with modifying potential irradiance occur in the denominator, the effect of angular adjustments on reflectance, R_i, is the inverse. That is, a given radiance value, L_i, will yield higher reflectance on a slope facing away from the Sun than the same L_i on a slope facing toward the Sun. This occurs because available incoming radiation is modeled to be less on the slope facing away from the Sun. The given radiance value indicates that proportionately more incoming light is being reflected there than on the slope facing the Sun, and the surface, therefore, is more highly reflective. The net effect of this transformation tends to remove some of the contrast created by topographic shading, so images appear somewhat "flatter." As it were, the distribution of pixel values is now on a spatially "level playing field."

The natural range of R_i should be 0.0 to +1.0, or by some order of magnitude (to scale reflectance from 0 to 1,000). Unfortunately, this reflectance model tends to overcorrect when *all* the following conditions are true: 1) surfaces face nearly directly opposite the Sun ($a_s - spect \approx 180°$); 2) slopes are steeper than the angle of the Sun above the horizon ($slope_i > 90 - z_s$); and 3) detected radiance, L_i, is above zero. In these cases, the product of the denominator evaluates to near zero and, with some level of detected L_i, the quotient R_i becomes unrealistically high (either positive or negative). This occurs because the algorithm assumes total potential for illumination comes only from Esi_b, and thus solar irradiance is essentially absent from areas in shadow. In reality, however, the situation demonstrates that some contribution to detected radiance, L_i, may come from reflected light off surrounding surfaces or the atmosphere, and not only from Esi_b directly. Overcorrecting may also arise from misregistration, error in the digital slope, and aspect models, or it may indicate clouds, where pixels obviously do not have appropriate slope and aspect angles associated with them.

Ignoring the known errors, which typically can be corrected or excluded from analysis, solutions to the steep shadowed slope problem are variable and potentially complicated. They generally only pertain to a small portion of a scene, however. If those areas are not widespread and/or do not interfere with a particular analysis, it is best to ignore them and mask out the overcorrected pixels ($R_i < 0.0$ or $R_i > 1.0$) by rescaling them to zero. Exclude them from subsequent calculations, generally, if such pixels are on steep sheltered slopes without sufficient vegetation to warrant concern in burn applications. (Assuming images over mountainous terrain are from mid-latitudes, within 6 weeks of summer solstice.)

If such pixels apparently interfere with acceptable accuracy of objectives, one can reclassify the slope dataset such that slope angles greater than or equal to the angle of the Sun above the horizon are reassigned to equal the Sun elevation angle minus 1:

$$\text{IF } (slope_i \geq 90 - z_i) \text{ THEN } (slope_i = 90 - z_i - 1)$$

This minimally alters the response curve of Esi_b on steep slopes over the range of aspects but prevents that term from being reduced to zero in the denominator. At the same time, it accommodates a small amount of irradiance (equivalent to 1 degree of slope) contributing to the brightness of those pixels, which may naturally come from indirect reflected light.

A third option is to filter the topographically corrected solar irradiance of the denominator to establish a lower near-zero limit. Values less than approximately 1 percent of Esi_b should be reassigned to a minimum level (the value of 0.01 is flexible and may be modified with experimentation) equal to about 1 percent of Esi_b:

$$\text{IF } (tEsi_b < 0.01^* \; Esi_b) \text{ THEN } (tEsi_b = 0.01^* \; Esi_b);$$

where $tEsi_b$ is the modified incoming solar irradiance per band that accounts for incidence angles from the Sun and the Earth's surface. To facilitate this, it may be necessary to create an interim raster dataset of $tEsi_b$ and then employ available GIS functions to make the reassignment. The resulting dataset is then reinserted in the algorithm to complete the reflectance calculation.

Pixels with zero radiance (no detected brightness) will not be affected by these two adjustments, as should be the case, because both the numerator and the quotient will evaluate to zero overall.

Other solutions to the problem involve expression of more complex geometry within the algorithm. At this time, we are not prepared to recommend any one in particular, but we would be interested in hearing about practical solutions that have been tried and found successful.

Atmospheric normalization

There are a number of solutions, and good literature exists on performance of different methods. Here, a relative normalization of one scene to another is undertaken, considering that results are based on band ratios, and geographic scope is typically limited to subsets of scenes. A list of procedural steps follows.

1. Determine if transmittance is a factor, and if so, which scene is most affected by atmospheric scattering. The scene less clear—the one with less transmittance—will be the one corrected and will become the independent variable in regression analysis performed later. Usually, this scene will exhibit brighter reflectance over dark targets, such as lakes, compared to values from the same targets in scenes with greater transmittance. Relative difference in transmittance can be determined quantitatively by comparing pixel reflectance sampled over dark targets. Lower transmittance also appears to decrease contrast, compared to scenes where the air is clear. The most affected bandwidths include the visible Bands (1, 2, and 3), so base comparisons on those bands to enhance differences. (Band 1 is most influenced by atmospheric factors, so use it when comparing single bands.) Compare bands between scenes individually as grayscales, in false-color combinations, or by their histograms. The scene with less transmittance should show less variance in the histogram and a shift to the right or brighter region.
2. Using both scenes for reference, digitize small polygons consisting of a few (50 to 200) pixels each, which collectively represent areas of low, mid-range, and high reflectance. Each polygon should be restricted to quasiinvariant targets that appear to have the same relative reflectance in both scenes. Targets should not be subject to seasonal changes or other disturbances that normally affect reflectance. Examples of acceptable targets include: 1) lakes or deep shadow for the dark sample; 2) high density mature conifer stands for the mid-range; and 3) rock, snow, or parking lots for the bright sample. Avoid areas that differ noticeably between scenes, such as where clouds occur, or where snowmelt patterns are not the same. Attempt to obtain sample polygons from within about one-quarter of the scene surrounding burn study area(s). Sample sizes should be in the range of four to eight polygons and 600 to 1200 pixels per level of reflectance, or more.
3. For each Band (4, 7) of each scene, extract pixel reflectance values that occur within the set of digitized polygons. Import them to statistics software capable of performing linear and quadratic regression. The statistics data file should sequentially contain a record for each pixel, with each pixel's reflectance values as the variables (Bands 4 and 7 of one scene, and Bands 4 and 7 of the other scene).

4. Perform curve-fitting operations on each band using both linear and quadratic models to associate the two dates. Assign the evidently less clear scene to the X axis (independent variable) and the scene with greater transmittance to the Y axis (dependent variable), per band. Make sure that scenes are properly assigned to dependent and independent variables by reviewing the regression coefficients. If they are not, reverse the order of the scenes in the regression analysis.
5. Notice which model best fits the data of each band by reviewing the regression statistics, and a scattergram of plots with regression lines overlaid. If possible, include a 98 percent confidence interval on those plots. Select the regression model that most adequately explains the intraband differences observed between scenes. This is a judgment call. Generally, one would not resort to the more complex quadratic model unless it obviously appeared to improve the fit throughout the distribution of points.
6. Remove widely deviant pixels from the sample before further analysis of each band. Such pixels likely differ between scenes due to reasons other than atmospheric clarity, such as phenology or some kind of disturbance. Use a broad confidence interval (CI) on the regression model just selected per band, such as 98 to 99 percent. Determine the breadth of those intervals per band in reflectance units plus-or-minus. Goodness of fit is generally quite high, since sampled pixels have been selected for their comparable reflectance. The typical r^2 should be in the range of 0.93 to 1.00, so even the 99 percent CI will usually be quite narrow. Construct a filter that eliminates records from the statistics data file, if a record has either Band 4 or Band 7 differing between scenes by more than the per-band CI. The objective is to define a set of pixels that shows a consistent trend in reflectance difference between the two scenes, caused only by atmospheric effects.
7. Rerun the selected regression model on the remaining pixels, with deviant pixels removed. Evaluate regression statistics and coefficients. If r^2 value is high, and coefficients indicate essentially no difference between the two distributions per band (for reflectance that is a *slope* in the range of 0.995 to 1.005, and an *offset* of ±0.010) then atmospheric normalization is probably not necessary, and one can use both original reflectance datasets to calculate NBR. If the r^2 value is too low, or elimination of deviant pixels leaves too small a sample size, consider redefining the sample polygons, and rerunning the regression. The initial sample may contain an excess of nonatmospheric effects or perhaps clouds.
8. Use regression coefficients just derived to transform the bands from the scene with greater atmospheric effects (independent variable above) and normalize them to the scene with apparently clearer air (dependent variable above). A linear transformation will have the form:

Equation LA-12

$$R_{Yi} = b_1 * R_{Xi} + b_0 \; ;$$

where, R_{Yi} is the new normalized per-pixel reflectance per band of the scene with less atmospheric clarity. R_{Xi} is the original per-pixel reflectance for that scene (the original independent variable above), b_0 is the regression coefficient of bias or offset, and b_1 is second regression coefficient for gain or slope. A quadratic transformation will have the form:

Equation LA-13

$$R_{Yi} = b_2 * R_{Xi}^2 + b_1 * R_{Xi} + b_0 \; ;$$

where variables are the same as above with the addition of b_2, which is the third regression coefficient for the square of the independent variable.

The resulting band reflectance data, R_{Yi}, are used in subsequent NBR calculations. Interactively on the graphics monitor, take a while to compare the results per band to the original reflectance data and to the scene not transformed. One should notice only subtle changes in the normalized data, but where visible, they should be in the direction that makes the corrected bands more similar to the scene with high atmospheric clarity, compared to the original bands with low clarity.

Finally, compare results to original band reflectance datasets. The results of regression transformation, though visually subtle, will be used in subsequent NBR calculations.

LANDSCAPE ASSESSMENT GLOSSARY

Azimuth angle—Reported in the Landsat scene header file, it is the angle in degrees from north of the position of the Sun when scene acquisition occurred, relative to scene center.

Band or Bandwidth—A discrete region of the electromagnetic spectrum, representing a range of wavelengths; the breadth of the region is the bandwidth. Sensors usually are designed to record the amount of energy detected within specific regions of the spectrum, hence the derivation of bands. In order of increasing wavelength, the spectrum begins with gamma rays and the ultraviolet, and progresses through the blue, green, and red zones of the relatively narrow visible range. The entire visible range expressed as one bandwidth is considered panchromatic and would appear like a black-and-white photograph. The near (NIR), middle (short-wave, SWIR), and thermal (long-wave, LWIR) infrared bandwidths follow in a broad region. Beyond infrared regions encompass much of what is used for communication, including microwaves, TV, and the longest, radio waves.

Burn severity—The degree or magnitude of environmental change caused by fire. The change may be represented by single or multiple biophysical variables on a continuous scale from no change to high change. The gradient may be partitioned into nominal levels, such as low, moderate, and high. For mesoscale landscape perspectives, it is the degree that fire affected an area or community, measured as a composite value over the horizontal and vertical dimensions of the area. In socioeconomic terms, burn severity is often measured by cost or human casualty incurred during and after a fire, including loss of resources. There are usually short- and long-term implications of burn severity, see **Fire effect**.

Community—For our purposes, an ecological community, consisting of all plants and animals, as well as the various inert materials, both organic and inorganic, which occupy an area. Generally, a community can be divided into multiple zones with different subcomponents (see **Stratum/strata**). Groups of communities often have similar, repeatable characteristics that lead to classification of specific community types, often based on dominant species, microclimate, and soil. Landscapes consist of assemblages of different communities.

Eccentricity factor—Variation in the radius of Earth orbit that accounts for daily deviation from an average circular orbit, as applied to **reflectance**.

Equation LA-14 $$d^2 = 1 / E_o \;;$$

where d^2 is the eccentricity factor, and E_o is the eccentricity correction quotient for day o.

Equation LA-15 $$E_o = (r_o / r)^2 \;;$$

where r_o is the Sun-to-Earth orbital radius on day o, and r is the mean orbital radius over a year period.

Edaphic—Characteristics resulting from properties of the soil.

Fire effect—Any result of fire. It may be related to biological or physical components of ecosystems, or to ecological processes that in turn impact biological or physical components. It may also be related to biophysical systems, such as communities, the atmosphere, or landscapes.

Fire effects, initial or first order—Those effects manifested on the biophysical components or systems that existed at the time of fire. First order fire effects are the direct result of combustion processes, including plant injury and death, fuel consumption, and smoke production (Reinhardt and others 2001).

Fire effects, long term or second order—Time-dependent responses to fire over the long term, where initial fire effects are influenced by many biophysical factors subsequent to the fire, such as: 1) seed-bank species and proximity to postfire seed sources; 2) localized site characteristics like topography and soils; 3) subsequent climate; and 4) secondary effects from erosion and mass wasting.

GIS—Geographic Information System(s). Integrated software, hardware, and data used to store and manipulate information that combines thematic and locational attributes about geographic features.

Herb—Annual, biennial, or perennial plants, including grasses, that do not develop persistent woody tissue, but tend to die back and regrow (or reseed) on a seasonal basis.

Histogram—A frequency distribution over a range of values. For example, the number of pixels that occur at each numeric value of reflectance. May be presented in tabular or graph form.

Hydrography—The geography of hydrologic features, principally surface waters comprising all variations of lakes, rivers, and streams; as well as the drainages within which these features are nested.

Irradiance—The quantity of light reaching Earth, as measured in energy units per unit area per bandwidth (watts per square meter per micron). The amount of incoming radiation available for detection.

Multispectral—Data received by a sensor, recorded as brightness values that occur within a few (usually four to 20) relatively narrow ranges, or **bandwidth**, of the electromagnetic spectrum. Each band is recorded independently but simultaneously from the same surface area, providing information about surface composition. The number of bands and the bandwidths define the sensor's spectral resolution. Spectral values recorded in many (100 to 300) relatively narrow bands are considered hyperspectral and more closely approximate the continuum of energy observed in the spectrum.

Normalized Difference Vegetation Index (NDVI)—A normalized difference of Landsat Band 4 (NIR) and Band 3 (visible red), expressed as:

Equation LA-16 $$NDVI = (R4\text{-}R3)/(R4\text{+}R3)$$

The index is directly related to the amount of green biomass, per unit area. It has been used as a measure of leaf area, primary plant production, and when temporally differenced, as an index of dryness or drought.

Pixel—Literally, "picture element." The smallest unit area that has a data value assigned to it. Pixels within an image generally are all the same size, and arranged in a contiguous rectangular grid of rows and columns. Spatial orientation of the grid can be registered to a map projection so that individual pixels may be located on the ground.

Radiance—The brightness detected by a sensor in a particular bandwidth.

Radiometric—Having to do with measurements related to the intensity of radiant energy.

Raster—A digital image stored in one of many grid cell formats, where the cells (pixels) are represented as binary numeric values referenced by byte position within the file. Byte position can be translated into pixel row and column such that the grid models some two-dimensional space.

Reflectance—For our purposes, a per-pixel ratio of the amount of reflected energy measured per bandwidth by the satellite, to the amount of available incoming solar radiation per bandwidth. The latter quantity is the exo-atmospheric solar **irradiance** per bandwidth, a constant, modified by the daily eccentricity of Earth-Sun distance and the incidence angle of sunlight striking Earth and reflecting back to the satellite. Incidence angles may simply incorporate the solar zenith angle derived from the Landsat scene header file, or may be refined by also including the solar azimuth angle, and the per-pixel slope and aspect angles derived from a Digital Elevation Model (DEM).

Scattergram—A two-dimensional plot of points with X and Y axes assigned respectively to an independent and a dependent variable. Point locations indicate the value observed in one variable at a given value of the other variable; for example, the Band 4 reflectance of a pixel before fire versus Band 4 reflectance of that same pixel after fire.

Spatial heterogeneity—The mix and diversity of identifiable landscape features, incorporating not only the types of features, but also their size, shape, and location in relation to each other. Useful dimensions or units include: number of different patches; patch size, shape, and diversity; fractal dimension (one of several ratios of patch size to perimeter distance); juxtaposition (a weighted length of edges surrounding a central area); and contagion (the degree of clumping). For burn heterogeneity, such measures indicate how complex a burn was, and the prevalence of particular levels of burning.

Spatial resolution—The aerial dimension of the smallest element that can be resolved, or identified on a map, image, or ground surface. For Landsat TM and ETM+ sensors, it is approximately 30 x 30 m^2, which constitutes a **pixel**. Smaller features, or parts of multiple features that co-occupy a single pixel, become averaged together to make up the overall spectral signature recorded for that area (see **Multispectral**).

Spectral signature—The combined values of one or more **bands** that uniquely define a particular area or feature, such as an individual pixel or a type of vegetation. The bands and the ways they are combined are highly variable and dependent on user objectives. It may be as simple as a range of values from one band, or as complex as involved mathematical algorithms incorporating many bands, as in clustering techniques. Usually statistical reliabilities are associated with signatures to help the analyst determine which ones best identify the features of interest.

Stratified sampling—Where the entire population to be sampled is divided into subgroups, and samples are drawn by rules pertaining to each subgroup. For the population of pixels representing a whole burn, one might divide the area by drainages or by perceived severity levels, and choose a number of sample points from each area. The draw might be done either randomly or in equal numbers per subgroup.

Stratum or strata—Referring to one or more layers of a community, arranged vertically and having a continuous sequential order from below ground to ground level, and from ground level to the top of the uppermost vegetative canopy. Strata typically are based on within-stratum similarities of physical organization, species composition, and/or microclimate. Heights of strata usually differ, increasing upward. A few too many strata may be used to characterize a given community, depending on recognizable traits and consistency of occurrence, as well as objectives for doing so. For burns, we identify strata that likely influence fire behavior and show potentially unique responses to burning.

Transmittance—For our purposes, a ratio of the amount of energy actually passing through the atmosphere and reaching the ground, to the maximum amount that can possibly reach the ground. It designates the clarity of the atmosphere, and is inversely related to the amount of atmospheric scattering. When transmittance equals 1, the air is perfectly clear. Progressively lesser values indicate increased scattering of light, as influenced by clouds, humidity, and particulates, including smoke. Areas of low transmittance generally appear brighter than areas of high transmittance, because the atmospherically scattered portions of light are not diminished by absorption from ground surfaces. Transmittance varies by **bandwidth**; a property of energy, such that capacity for atmospheric penetration increases with wavelength. For Landsat, this means that infrared Bands 4 through 7 are less influenced by scattering factors than visible bands.

UTM—The Universal Transverse Mercator is a map projection. Widely used in natural science applications, it is suitable for maps of 1:100,000 and greater scale, (1:24,000). Each hemisphere of the world is divided into 60, 6-degree, zones by longitude. Within each zone, the reference is an X,Y equidistant grid in meters, with origin at the lower left zone corner (western most point on the equator). Coordinate pairs are given in meters northing and easting (for example, 5437689N, 278334E), increasing from the origin to the north and to the east, respectively. For more UTM information, see:

http://erg.usgs.gov/isb/pubs/factsheets/fs07701.pdf

Vector—Geographic data represented as numeric X, Y coordinates, and usually some attribute identifier. Vector data define features by point, line, or polygon topology, and are displayed as such on maps or graphics.

Zenith angle—The angle of the Sun in degrees from zenith (the position directly overhead at scene center) when scene acquisition occurred. The Sun elevation angle, *e*, is reported in the Landsat scene header file as degrees above the horizon. To obtain the zenith angle, subtract that value from 90 degrees:

$$(z_s = 90 - e_s).$$

RECENT LANDSAT SATELLITES

Landsat 5

Launched in 1984, Landsat 5 carries the Thematic Mapper (TM), which records 30-m data in six spectral Bands and 60-meter data in one Band. The Bands include the blue, green, red, and near infrared (NIR) portions of the spectrum (Bands 1 to 4, respectively), and two Bands (5 and 7) in the middle infrared, or short-wave infrared (SWIR), range. These all measure reflected energy. The final Band (6) records emitted thermal infrared or long-wave infrared (LWIR) that registers heat. All bands are spatially coregistered. The orbit is near-polar, with a swath width, or path, recorded across about 180 km. The continuous stream of data for each swath is segmented out into approximately square areas called "scenes" for purchase. A scene covers roughly 32,400 km^2 (180 x 180 km) of the Earth's surface. The orbital sequence is continual and iterative, such that repeat coverage for any particular swath is 16 days. Scenes initially are path-oriented—but one can request various levels of geo-rectification—to register a dataset of all bands to a user-specified map projection. Both side-lap and end-lap occurs between adjacent scenes. The latter is typically constant at about 5 percent, while the former increases from the equator toward the poles, within a range of about 5 to over 60 percent. Regions that fall within overlap areas can have multiple scene dates for expanded temporal coverage outside of the 16-day interval.

Recent reduction in Congressional appropriations may necessitate decommissioning Landsat 5. As a consequence, this source may not be available in the near future. For more information visit the Landsat 5 Web site at:

http://www.earth.nasa.gov/history/landsat/landsat5.html

Marketing and pricing of Landsat 5 data used to be fairly complicated. Basically, there were two exclusive sources for the U.S. scenes more that 10 years old, and all scenes previously purchased by the Federal Government were available through the USGS EROS Data Center (EDC) outside Sioux Falls, SD. The cost was fixed and relatively inexpensive, ranging between $600 and $800, depending on the postprocessing options requested by the buyer. Scenes less than 10 years old, and not previously purchased, were sold by a private company, Space Imaging Corp., formerly EOSAT Corp. Pricing was roughly double the above, at about $1,200 to $1,600 per scene. One could also order these scenes through EDC. However, the cost included the normal EDC processing, plus a tape origination fee, plus a fee for every scene that preceded the scene of interest on the tape. Since the latter was highly variable, the least cost alternative had to be determined on a case-by-case basis. Presently, all Landsat data are marketed by EDC, and costs have been fixed at lower prices. Data are distributed on CD and various tape media.

For ordering and viewing available Landsat 1 through 5 scenes, check the following Web site:

http://edcsns17.cr.usgs.gov/EarthExplorer/

Space imaging continues to sell derived Landsat 5 products, such as map-registered photographs from space, and products from other satellites; their Web site is:

http://www.spaceimaging.com/products/25ms.html

Landsat 7

Launched in 1999, Landsat 7 carries an Enhanced Thematic Mapper Plus (ETM+) sensor. It records essentially the same spectral and spatial characteristics for Bands 1 through 7 as the TM (above). In addition, ETM+ has a 15-meter panchromatic band, Band 8, spanning the whole visible spectrum (blue through red) in one bandwidth, and an additional thermal infrared band, Band 9 at 60-m resolution. Orbital and scene characteristics are similar to Landsat 5, with closely overlapping paths. Overpasses between the two satellites are staggered by 8 days. This provides more frequent coverage for a given area, at least as long as both satellites remain operational. As of May 2003, Landsat 7 developed a scan line corrector problem, which leaves a regular pattern of missing lines within the scenes. The problem has a negative impact on fire-related applications, but some of that data may still be useful.

For more information about Landsat 7, see:

http://landsat7.usgs.gov/

http://landsat.gsfc.nasa.gov/

All Landsat 7 data is available through the USGS EROS Data Center near Sioux Falls, SD. Prices for data collected before May 2003 range between $475 and $800, depending on buyer-specified postprocessing options. Those include four levels of radiometric and geometric correction. The highest level, "precision corrected," is recommended because some of these procedures are difficult to perform "in-house," and the added cost is low to ensure that all data holdings have been treated in standard and well documented ways. Data are distributed on CD, various tape media, or by ftp over the Internet. There are options for data after May 2003, with the scan line corrector problem, at much lower prices. Consult the USGS EROS Data Center for up-to-date information.

For ordering and viewing available Landsat 7 scenes, contact either of the two Web sites:

http://edcdaac.usgs.gov/landsat7/

http://edclxs2.cr.usgs.gov/

OTHER REMOTE SENSING DATA SOURCES

Several remote sensing technologies besides Landsat may be available to address fire management objectives. Applicability depends on scale, scope, and cost requirements, which may be different from those of FIREMON Landscape Assessment. For example, continental geographic coverage and daily sampling frequency can be obtained at low cost from AVHRR data. The resolution is 1 km, however, and may be too course for local resource managers.

MODIS, a relatively new sensor geared mostly to global dynamics, may be suited to landscape monitoring of burned areas, but has limited resolution of 250 m in two bands. The remaining 34 bands have resolutions of either 500 or 1,000 m. Currently released data products are provisional data sets, primarily of interest to the research community. Standardization of these products may not be optimal as incremental improvements are still occurring. Moreover, data are not continuously archived, and there is limited availability over designated target sites. At this writing, the data are free however, and may be worth considering for burn monitoring in some areas.

Detail finer than Landsat can be achieved with 1- to 20-m resolution from a host of airborne or satellite sensors, including AVIRIS, ASTER, SPOT, and IKONOS. Price is significantly greater than Landsat per unit area. However, these might be appropriate for individual case studies of high ecological or socioeconomic significance, where interregional standardization is not so much a concern. Generally, none provide continual continent-wide coverage, and acquisition is intermittent. Missions are contracted project to project and prescheduled at designated target areas. Acquisition is usually limited to a few attempts, so unsuitable conditions, such as excessive cloudiness, can force cancellation of a mission when adequate data cannot be had in the allotted time. Because future fire locations cannot be known, there also is little chance to acquire preburn information. That notwithstanding, some of these sensors may be added to FIREMON methodology in the future, as they become further developed and evaluated for routine burn monitoring in a variety of ecosystems.

FIREMON LA BR Cheat Sheet

The Normalized Burn Ratio (NBR)—Brief Outline of Processing Steps

Acquire adequate Landsat TM or ETM+ scenes:

- Determine timing requirements: *initial* or *extended* assessment.
- Pre- and postfire scenes should match phenologically as much as possible.
- Search for available scenes using Web browsers
  - Landsat 7 ETM+: http://edclxs2.cr.usgs.gov/L7ImgViewer.shmtl/
  - Landsat 5 TM: http://earthexplorer.usgs.gov/ (follow links to Landsat TM)
- Check availability of already-purchased data before ordering.
- Get Terrain Corrected data.

With data in hand, explore data in false-color composite images, study burn characteristics.
Transform raw data to *Radiance* (L_i) and "at-satellite" *Reflectance* (R_i) for Bands 4 and 7.

$$L_i = DN_i * G_b + B_b; \qquad R_i = (L_i * \pi * d^2) / (\mathrm{Esi}_b * \cos(z_s))$$

DN_i = per-pixel raw brightness value.
G_b *and* B_b = per-band gain and bias from scene header.
d^2 = daily earth-sun eccentricity from lookup table.
Esi_b = per-band exoatmospheric solar irradiance from published L5 and L7 tables.
z_s = per-scene solar zenith angle (90-solar elevation angle reported in scene header).

Determine if atmospheric normalization is necessary, and if so, do it if for Bands 4 and 7.
Generate an NBR image for each scene, pre- and postfire:

$$NBR = (R_4 - R_7) / (R_4 + R_7);$$

Generate the differenced (or delta) NBR:

$$dNBR = NBR_{prefire} - NBR_{postfire}$$

This isolates burned from unburned areas, provides a quantitative measure of absolute change in NBR. Practical data range ≈ –500 to +1,300 when scaled by 10^3.
Apply a linear grayscale to the data range of –800 to 1,100, and study this image carefully.
Define the burn perimeter using combined automated and on-screen digitizing from the d***NBR***.
Make an initial cut at severity thresholds in false color. A seven-tiered configuration may be useful. Ordinal severity levels and example range of
NBR (scaled by 10^3) are shown:

Ordinal severity levels and example range of dNBR (scaled by 10^3), to the right.

Severity level	dNBR range
Enhanced regrowth, high	–500 to –251
Enhanced regrowth, low	–250 to –101
Unburned	–100 to +99
Low severity	+100 to +269
Moderate-low severity	+270 to +439
Moderate-high severity	+440 to +659
High severity	+660 to +1300

(dNBR value ranges are flexible; scene-pair dependent; shifts in thresholds ±100 points are possible. dNBR less than about –550, or greater than about +1,350 may also occur, but are *not* considered burned. Rather, they likely are anomalies caused by misregistration, clouds, or other factors not related to real land cover differences.)

FIREMON LA CBI Cheat Sheet

STRATA

Substrates—Inert surface materials of soil, duff, litter, and downed woody fuels.
Herbs, Low Shrubs and Trees—All grasses + forbs, and shrubs + small trees <3 ft (<1 m).
Tall Shrub and Trees—Shrubs and trees 3–16 ft (1–5 m) tall.
Intermediate Trees (pole-size, subcanopy)—Trees between tall shrubs/trees and upper canopy, approximately 4–10 inches (10–25 cm) diameter, and 25–65 ft (8–20 m) tall. May be stratified heights and extend to upper canopy, but crowns receive little direct sunlight. Size is relative to upper canopy and varies by community. If this size is upper canopy, count as intermediate trees.
Big Trees (mature, dominant and co-dominant, upper canopy)—Larger than intermediate trees, occupy upper canopy, receive direct sunlight; tallest may extend above average big-tree level.
Understory—Substrates, herbs/low shrubs+trees, tall shrubs+trees.
Overstory—Intermediate and big trees.
Total Plot, or Overall—All strata of the plot combined.

GENERAL

Prefire Exposed Soil/Rock is considered unburned if there is no sign of overlying substrates or vegetation that burned. Avoid sites with >50% exposed prefire soil/rock, see guidelines.
Rehab Site—Mulch or other does not count, estimate as if that was not present. Planted, growing vegetation can be tallied where appropriate, but not as new colonizers. A specific factor may not be rated if is not relevant, shows inconsequential presence or insignificant indication of severity (write in N/A for not applicable), or when effects are unclear and cannot be reasonably judged (write in UC for uncertain).
Percent Plot Area Burned—Record the percent surface area (burned substrates and low-growing plants) showing any impact from fire for the 98-ft (30-m) diameter plot, and for the nested 66-ft (20-m) plot, if that is used for the understory.
Prefire Variables—Report cover (percent area), depth (inches) and density (number of trees) plot-wide as if before fire. Consider burned evidence + unburned areas within plot or nearby; reasonable approximation of prefire conditions. If too difficult to estimate, write in UC for uncertain.
Enhanced Growth Factors—100 percent + percent productivity above that, judged to be fire-enhanced; regard amount of green biomass in terms of cover, volume and density. If plots show about the same or less productivity than before fire, then enter as not applicable (N/A). If plot shows enhanced growth, then enter the percent productivity that is augmented by fire, with 100 percent being the same postfire productivity as prefire (for example, 200 percent represents double the estimated prefire productivity); write in UC if uncertain.

SUBSTRATE RATING FACTORS
Do not count litter or fuels built up after fire.

Litter/Light Fuel—Relative amount consumed of leaves, needles, and < 3-inches (<7.6-cm) diameter wood on the ground at time of fire. Not new litter-fall. Count litter/light fuel even if it occurs under living plants.
Duff condition—Relative amount consumed and charring of decomposed organic material lying below the litter. Not fine root mass. Count duff even if it occurs under living plants.
Medium Fuel—Consumption of down woody fuel between 3–8 inches (7.6–20.3 cm).
Large Fuel—Loss and charcoal from down woody fuel >8-inch diameter (20.3 cm). Base both classes on change to fuel load. Omit or join as one if either fuel class < 5 percent plot cover, see text. Include stumps in appropriate size class, if relevant.
Soil Cover/Color—New exposed soil and color change; lightening at moderate to high, ~10 percent red at high severity—overlook ash. Consider soil or rock surface *not* covered by litter, duff or low herbaceous cover less than about 30 cm. If such occurs under taller shrubs and trees, count it.

HERBS, LOW SHRUBS AND TREES LESS THAN 3 FEET (1 METER) RATING FACTORS

Percent Foliage Altered—Only low shrubs and trees (<3 ft), prefire live or dead cover that are newly brown, black or consumed. Ignore resprout.
Frequency Percent Living—Percent of prefire vegetation that is still alive after fire, based on number plot-wide; survivorship, not cover, not new seedlings. Include unburned as well as burned, resprouting perennial herbs, low shrubs and trees (<3 ft) pot-wide. Include all green vegetation as well as burned plants that have not had enough time to resprout but remain viable. Burned plants may need to be examined for viable growth points. Do not include new plants from seed or suckers.
Colonizers—Potential dominance 2–3 years postfire of new (native or exotic) plants from seed; includes herbs and tree seedlings, plus aspen or other tree-to-shrub suckers, and nonvascular plants (for example, thistle, fireweed, pokeweed, ferns, moss, fungi, seedlings of lodgepole pine, slash pine, western larch, many weedy spp.). Rate only if spp. response to fire is known.

FIREMON LA CBI Cheat Sheet (cont.)

Species Composition/Relative Abundance—Change in spp. and/or relative abundance of spp. anticipated 2–3 years postfire. How much does postfire spp. composition resemble prefire stratum? Consider presence of new or absence of old spp., plus how dominance is spread across spp.

TALL SHRUBS AND TREES 3 TO 16 FEET (1 TO 5 METERS) RATING FACTORS

Percent Foliage Altered—Percent prefire live-or-dead crown volume (leaves, stems) newly brown, black or consumed. Ignore new resprout; it does *not* lessen the amount of prefire foliage altered.

Frequency Percent Living—Percent of prefire tall shrubs/trees that are still alive after fire. This is a measure of survivorship based on numbers of individuals. Include unburned as well as burned but viable tall shrubs/trees 3–6 ft (1–5 m) tall plot wide; examine growth points for viability if needed. Do not include new plants from seed or suckers. Account for potential mortality that could occur up to 2 years postfire.

Percent Change in Cover—Overall *decrease* in cover of tall shrubs/trees between 3 and 16 ft tall (1 and 5 m), relative to the area occupied by those plants before fire. Count resprouting from plants that burned, plus the unburned plants as cover that lessens the amount of decrease in cover. Do not include suckers or plants newly germinating from seeds.

Species Composition/Relative Abundance—Change in spp. composition and/or relative abundance of spp. anticipated 2 to 3 years postfire.

INTERMEDIATE AND BIG TREE RATING FACTORS (COMBINED)

Percent Unaltered (green)—Percent prefire live-or-dead crown volume unaltered by fire. Include new resprout from burned crowns, not from bases.

Percent Black (torch)—Percent prefire live-or-dead crown volume that actually caught fire (black or consumed stems, leaves). May or may not be viable postfire; resprout from black crowns does not lessen percent black. At high severity, consumption of fine branching is evident. Include deciduous blackened crowns.

Percent Brown (scorch)—Percent prefire live crown volume affected by scorch or girdle without direct flame contact. Brown is due to proximal heating, where foliage did not catch fire. Includes delayed mortality, insect damage, and brown foliage that has fallen to ground.

Percent Canopy Mortality —Percent prefire live canopy volume made up by trees killed directly or indirectly by fire within 1–2 years. Proportion of a plot's total once-living canopy lost to dead trees (include insect/disease kill) in relation to total prefire canopy volume.

Char Height—Mean char height from ground flames averaged over all trees. The mean is halfway between upper and lower heights on a tree. Include unburned (char height = 0) and burned trees ***only*** when char height is discernable. Do ***not*** include black from crown fire; enter N/A for most crown fire burns.

RECORD FOR EACH OVERSTORY STRATUM, BUT DO NOT COUNT IN CBI SCORES

Percent Girdled (at root or lower bole)—Percent of trees effectively killed by heat through the lower bark, sufficient to kill cambium around lower boles or buttress roots. Include trees either dead or likely to die within 1–2 years. Do not include trees killed by torch or scorch to crown. May or may not char through bark and into the wood; may have loose sloughing bark in 1–2 years.

Percent Felled (downed)—Percent live-or-dead trees, that were standing before fire but now are on the ground. Usually from wind throw after fire, they exhibit fresh up-turned root masses, and different charring patterns than trees that were down when fire occurred.

Percent Tree Mortality—Percent of once living trees on the plot that were killed by the fire, based on number of trees. Suspected insect and disease effects also may be included, if such contributed to killing whole trees relatively soon after fire (for example, within 1–2 years).

RATING ADVICE

Factors that are not applicable or cannot be resolved in a plot are not rated; they are omitted from that plot's composite ratings. Moreover, if there is much uncertainty about how a specific factor should be rated, or whether it is even relevant to the plot, then that factor should be left unranked. Only the number of rated factors is used to compute averages. If a factor is not rated, enter not applicable (N/A) or uncertain (UC) on the CBI data form. Do not just leave the field blank; such factors are not part of the CBI average, but one wants to know whether these factors were actually assessed and it was decided not to rate them, or just accidentally overlooked and skipped. Zeros, on the other hand, are valid entries and do get averaged into composite scores. Zeros should be used when a rating factor is applicable and exhibits an unburned condition. A zero represents no detected change in an observable factor.

FIREMON LA Form

BURN SEVERITY -- COMPOSITE BURN INDEX (BI)

PD - Abridged	Examiners:			Fire Name:	
Registration Code		Project Code		Plot Number	
Field Date mmddyyyy	/ /	Fire Date mmyyyy	/		
Plot Aspect		Plot % Slope		UTM Zone	
Plot Diameter Overstory		UTM E plot center		GPS Datum	
Plot Diameter Understory		UTM N plot center		GPS Error (m)	
Number of Plot Photos		Plot Photo IDs			

BI – Long Form	% Burned 100 feet (30 m) diameter from center of plot =	Fuel Photo Series =

STRATA RATING FACTORS	BURN SEVERITY SCALE							FACTOR SCORES	
	No Effect	**Low**		**Moderate**		**High**			
	0.0	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**		
A. SUBSTRATES									
% Pre-Fire Cover: Litter = Duff = Soil/Rock = Pre-Fire Depth (inches): Litter = Duff = Fuel Bed =									∑ =
Litter/Light Fuel Consumed	Unchanged	--	50% litter	--	100% litter	>80% light fuel	98% Light Fuel		
Duff	Unchanged	--	Light char	--	50% loss deep char	--	Consumed		N =
Medium Fuel, 3-8 in.	Unchanged	--	20% consumed	--	40% consumed	--	>60% loss, deep ch		
Heavy Fuel, > 8 in.	Unchanged	--	10% loss	--	25% loss, deep char	--	>40% loss, deep ch		X̄ =
Soil & Rock Cover/Color	Unchanged	--	10% change	--	40% change	--	>80% change		
B. HERBS, LOW SHRUBS AND TREES LESS THAN 3 FEET (1 METER):									
Pre-Fire Cover = % Enhanced Growth =									∑ =
% Foliage Altered (blk-brn)	Unchanged	--	30%	--	80%	95%	100% + branch loss		
Frequency % Living	100%	--	90%	--	50%	< 20%	None		N =
Colonizers	Unchanged	--	Low	--	Moderate	High-Low	Low to None		
Spp. Comp. - Rel. Abund.	Unchanged	--	Little change	--	Moderate change	--	High change		X̄ =
C. TALL SHRUBS AND TREES 3 to 16 FEET (1 TO 5 METERS):									
Pre-Fire Cover = % Enhanced Growth =									∑ =
% Foliage Altered (blk-brn)	0%	--	20%	--	60-90%	> 95%	Signifcnt branch loss		
Frequency % Living	100%	--	90%	--	30%	< 15%	< 1%		N =
% Change in Cover	Unchanged	--	15%	--	70%	90%	100%		
Spp. Comp. - Rel. Abund.	Unchanged	--	Little change	--	Moderate change	--	High Change		X̄ =
D. INTERMEDIATE TREES (SUBCANOPY, POLE-SIZED TREES)									
Pre-Fire % Cover = Pre-Fire Number Living = Pre-Fire Number Dead =									∑ =
% Green (Unaltered)	100%	--	80%	--	40%	< 10%	None		
% Black (Torch)	None	--	5-20%	--	60%	> 85%	100% + branch loss		N =
% Brown (Scorch/Girdle)	None	--	5-20%	--	40-80%	< 40 or > 80%	None due to torch		
% Canopy Mortality	None	--	15%	--	60%	80%	%100		X̄ =
Char Height	None	--	1.5 m	--	2.8 m	--	> 5 m		
Post Fire: %Girdled = %Felled = %Tree Mortality =									
E. BIG TREES (UPPER CANOPY, DOMINANT, CODOMNANT TREES)									
Pre-Fire % Cover = Pre-Fire Number Living = Pre-Fire Number Dead =									∑ =
% Green (Unaltered)	100%	--	95%	--	50%	< 10%	None		
% Black (Torch)	None	--	5-10%	--	50%	> 80%	100% + branch loss		N =
% Brown (Scorch/Girdle)	None	--	5-10%	--	30-70%	< 30 or > 70%	None due to torch		
% Canopy Mortality	None	--	10%	--	50%	70%	%100		X̄ =
Char Height	None	--	1.8 m	--	4 m	--	> 7 m		
Post Fire: %Girdled = %Felled = %Tree Mortality =									

Community Notes/Comments:	CBI = Sum of Scores / N Rated:	Sum of Scores	N Rated	CBI
	Understory (A+B+C)			
	Overstory (D+E)			
	Total Plot (A+B+C+D+E)			

% Estimators: **20 m Plot:** 314 m^2 1% = 1x3 m 5% = 3x5 m 10% = 5x6 m
30 m Plot: 707 m^2 1% = 1x7 m (<2x4 m) 5% = 5x7 m 10% = 7x10 m

After, Key and Benson 1999, USGS NRMSC, Glacier Field Station.
Version 4.0 8 27, 2004

Strata and Factors are defined in FIREMON Landscape Assessment, Chapter2, and on accompanying BI "cheatsheet." www.fire.org/firemon/lc.htm