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Remote sensing sensitivity to fire severity and fire recovery

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ABSTRACT: The paper examines fundamental ways that geospatial data on fire severity and recovery are influenced by conditions of the remote sensing. Remote sensing sensitivities are spatial, temporal and radiometric in origin. Those discussed include spatial resolution, the sampling time of year, and time since fire. For standard reference, sensitivities are demonstrated with examples drawn from an archive of burn assessments based on one radiometric index, the differenced Normalized Burn Ratio. Resolution determines the aggregation of fire effects within a pixel (*alpha variation*), hence defining the detected ecological response, and controlling the ability to determine patchiness and spatial distribution of responses throughout a burn (*beta variation*). As resolution decreases, alpha variation increases, extracting beta variation from the complexity of the whole burn. *Seasonal timing* impacts the radiometric quality of data in terms of transmittance, sun angle, and potential for enhanced contrast between responses within burns. Remote sensing sensitivity can degrade during many fire seasons when snow, incomplete burning, hazy conditions, low sun angles, or extended drought are common. Time since fire (*lag timing*) most notably shapes severity detection through the first-order fire effects evident in survivorship and delayed mortality that emerge by the growth period after fire. The former effects appear overly severe at first, but diminish, as burned vegetation remains viable. Conversely, the latter signals vegetation that appears healthy at first, but is damaged by heat to the extent that it soon dies. Both responses can lead to either over- or under-estimating severity, respectively, depending on fire behavior and pre-fire composition unique to each burned area. Based on implications of such sensitivities, three sampling intervals for short-term burn severity are identified; *rapid*, *initial*, and *extended assessment*, sampled within ca. two weeks, two months, and depending on the ecotype, from three months to one year after fire, respectively. Jointly, remote sensing conditions and the way burns are studied yield different tendencies for data quality and information content that impact the objectives and hypotheses that can be studied. Such considerations can be commonly overlooked, but need to be incorporated especially in comparative studies, and to build long-term reference databases on fire severity and recovery.

1 INTRODUCTION

While wildfire remote sensing today encompasses a wide assortment of approaches and content, this paper focuses on basic spatial and temporal factors that, in general practice, affect detection and definition of fire severity and recovery. The paper is meant to be conceptual, and principles are intended to apply across a broad spectrum of remote sensing approaches, recognizing that some may have unique properties or additional sensitivities. Topics deal mostly with ecological aspects of burned areas, and not socio-economic impacts that can also be associated with wildfire severity, such as damage to infrastructure and human casualty. The terms burn severity and fire severity are used interchangeably to define conditions resulting from fire, recognizing there may be traditional distinctions (Agee, 1993; DeBano *et al.*, 1998; McPherson *et al.*, 1990; Romme, 1980).

Burn remote sensing has a basic goal to gather reliable site-specific information over at least significant portions of impacted areas. A common challenge is to employ standard protocols to ensure comparable results from area to area and over time. The ability to standardize and compare results depends in large part on understanding the sensitivity of remote sensing to conditions that influence assessment, which is multi-dimensional, and not always straightforward. Sensitivities of remote sensing in such efforts depend upon objectives, which can vary from quite general and simple to very specific and inherently more complex (Table 1). Often coincident with complexity is increasing difficulty and uncertainty, such that the effort to develop more specific information about fires is often accompanied by lessened reliability. Thus, remote sensing sensitivity depends on the intended content, quality and detail of desired information.

Table 1. A relative rank ordering of information often useful for burn research and management. Complexity, difficulty, and uncertainty in remote sensing tend to increase in the matrix from upper left to lower right.

	Generally increasing detail		
Generally increasing specificity	**Low**	**Medium**	**High**
Burn Perimeter	1	2	3
Areas burned and not burned	2	3	4
Nominal burn categories, e.g. low severity under burn	3	4	5
A continuous scale of burn magnitude	4	5	6
Specific fire effects, e.g. percent duff consumption	5	6	7
Secondary effects, e.g. erosion, persistence of effects	6	7	8

In all cases, there are certain factors that directly influence results. These can be partitioned into two general arenas; those physically based in the remote sensing systems, and those more specifically traced to wildfire ecology and ensuing responses. The former include factors important to virtually any remote sensing application. Interacting with the two are perhaps four conditions of the remote sensing approach that can either constrain or bias the resolution of severity (Table 2).

Table 2. Factors affecting remote sensing of fire severity and recovery. Those discussed in this paper are italicized.

	Fire Independent	**Fire specific**
Spatial	*resolution*	*aggregation of effects*
	autocorrelation	*patch size*, contagion
Temporal	*site phenology*	*time since fire*
	moisture content	*fire seasonality*
	sun angle, snow	*fire completion*
	sampling interval	
Radiometric	*transmittance*	specific bandwidth response
	bandwidths	*in-burn range of variation*
	reflectance	smoke
Geographic	georectification	*elevation gradient*
	registration	*ecotype properties*

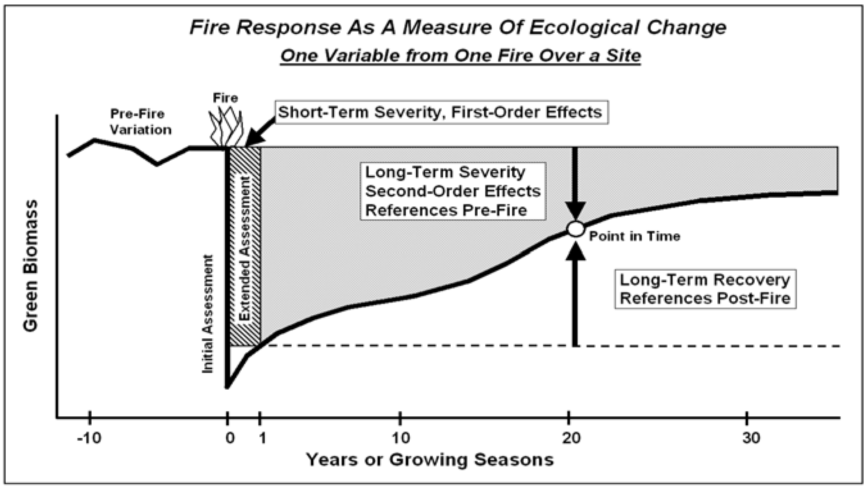
To illustrate the affect of sensitivity-factors on burn severity detection and definition, and as a common reference for comparison, one index of severity is used throughout, the differenced normalized burn ratio, delta-NBR or dNBR (Key and Benson, in press; van Wagtendonk *et al.*, 2004). Cases were extracted from an archive of assessments developed by the author over the last decade using 30-meter Landsat TM and ETM+ band reflectance data. The dNBR provides a continuous scale of difference that can be related to a magnitude of ecological change, which offers a conceptual model for burn severity. The dNBR is scaled by 1000 in this paper for the ease of interpreting integer values. Since about 2001, dNBR has been broadly applied in operational burned-area assessment by land management agencies in the U.S. (USDOI EDC, 2005; USFS RSAC, 2005).

2 A BRIEF CONCEPTUAL MODEL OF SEVERITY AND RECOVERY

The context for discussion of remote sensing sensitivity is that fire severity and recovery measure change from pre-fire and near-term post-fire conditions, respectively. Figure 1 displays a hypothetical response in just one variable. In nature, potentially a large number of variables are affected by fire. Each constitutes an individual *fire effect*; with unique dynamics that likely differ but continue to track magnitudes of fire-caused change. A second context is that severity and recovery, though possibly represented by just one effect, actually encompass all the responses within some defined area to gauge overall condition and summarize fire's impact. This is appropriate because: 1) many fire effects are very difficult to remotely sense individually; 2) effects that can be monitored individually have unique remote sensing parameters to measure stand-alone responses in lieu of severity; 3) fire can affect each component of the ecological community differently, and there is value in knowing the comprehensive impact; and 4) just one or two individual effects may not represent the condition of the area as a whole.

In Figure 1, the degree of change representing severity or recovery is a continuum against time. *First-order effects* are consequences to ecological components or conditions that existed before fire. The interval for sampling first-order effects is relatively short following fire, as many effects fade and become altered by biophysical processes, hence the reference to *short-term severity*, commonly regarded as burn severity. Fire effects initiate the interval of *recovery*, and provide the reference points from which to measure it. Many processes follow that control recovery, encompassing all new biophysical elements and conditions arising on site. Recovery intervals can be very long or relatively short, depending on the ecotype (Grau and Veblen, 2000; Abrahamson, 1984; Huddle and Pallardy, 1999). At any point during recovery, its complement can be defined as *long-term severity*, gauging status in relation to the site's pre-fire state. Some processes during the period can be viewed as *second-order effects* and constituents of long-term severity (Diaz-Delgado *et al.*, 2002). They include processes like erosion that are not significantly present before fire, but develop indirectly after fire and potentially alter the trajectory of recovery.

Figure 1. A conceptual model of fire severity and recovery that is dynamic over time.



3 SPATIAL SENSITIVITY

Spatial factors affect remote sensing of burns through interaction between resolution and the responses possible to detect (Chen, 1999; Liang, 2000). The detectable effects include variation that occurs within the minimum sampling unit, as well as between units, that is, throughout an entire burn. These sources are the intra- and inter-site variation in severity, respectively, introduced here as *alpha* and *beta variation*. The terms can be considered analogous to concepts of within-habitat and between-habitat diversity, or alpha and beta diversity, respectively (Macarthur, 1965).

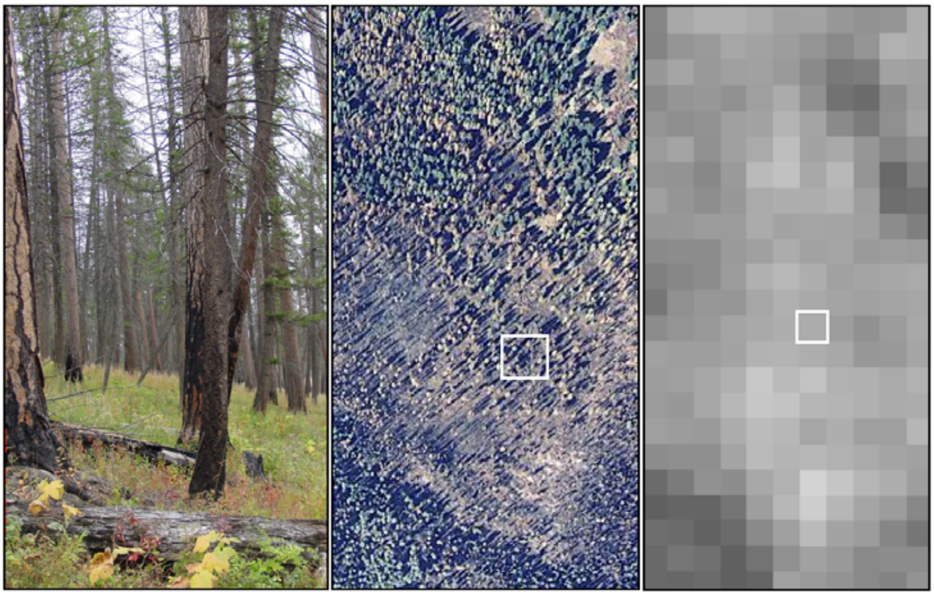
3.1 *Alpha variation (intra-site)*

In Figure 2 left, the *in situ* view reveals detail that can be measured throughout a 30x30 m site. Here, effects such as char height on each tree, and survivorship of individual understory species can be separated out and used either individually or collectively to establish the burn severity. At 0.3 to 1.0 m resolution (center), some alpha variation is retained, like scorch to individual tree crowns, but the number of severity indicators is reduced. General survivorship and consumption patterns in the understory still can be assessed separately from the overstory, but understory effects predominantly represent overall conditions rather than species-specific responses. The site, however, now appears in context with surroundings, which enables spatially uninterrupted assessment over broader areas (beta variability). As resolution decreases to 30-meter (right), components of the site are not individually detectable, being reduced to a single, summary value. All understory and overstory effects combine to yield a synoptic average condition. Response at this level is a spatially and compositionally integrated quantity referred to as *site severity*.

A question arises as to what response attributes are captured by remote sensing at the 30-meter site level? If the quantity is a blend of individual effects as described, field measures should reflect the spatial extent and aggregation recorded by remote sensing. This is the rationale behind the Composite Burn Index (CBI) derived from an average of 4-5 rating factors per each of five potential strata in the ecological community, where each factor in turn is an average across the area of the plot (Key and Benson, in press). Once site severity is determined, field measures and remote sensing values should be well matched for content and effectively correlated.

Secondarily, those values could be related back to individual effects, such as duff consumption, but with varying degrees of reliability. At very low or very high severity, such associations can be relatively certain. In middle ranges, where alpha variation on the ground can be high, individual effects are not expected to be uniform (Peterson and Stow, 2003; Schimmel and Granstrom, 1996). Fire intensity and ecological response can vary over the 30-meter pixel, while each stratum and component may be affected differently. It follows that similar magnitudes of site severity can result from different combinations of effects and burn pattern within the site. Thus, ability to remotely sense individual effects, though partly limited by radiometric factors, is spatially constrained by alpha variation.

Figure 2. The stepwise aggregation of fire effects as spatial resolution decreases. From left to right, field photo taken about 1 year post-fire; color aerial photo 1 month post-fire; dNBR image using data from1 month post-fire. White squares, roughly 30x30 m, denote approximate location of the site shown at left.



3.2 *Beta variation (inter-site)*

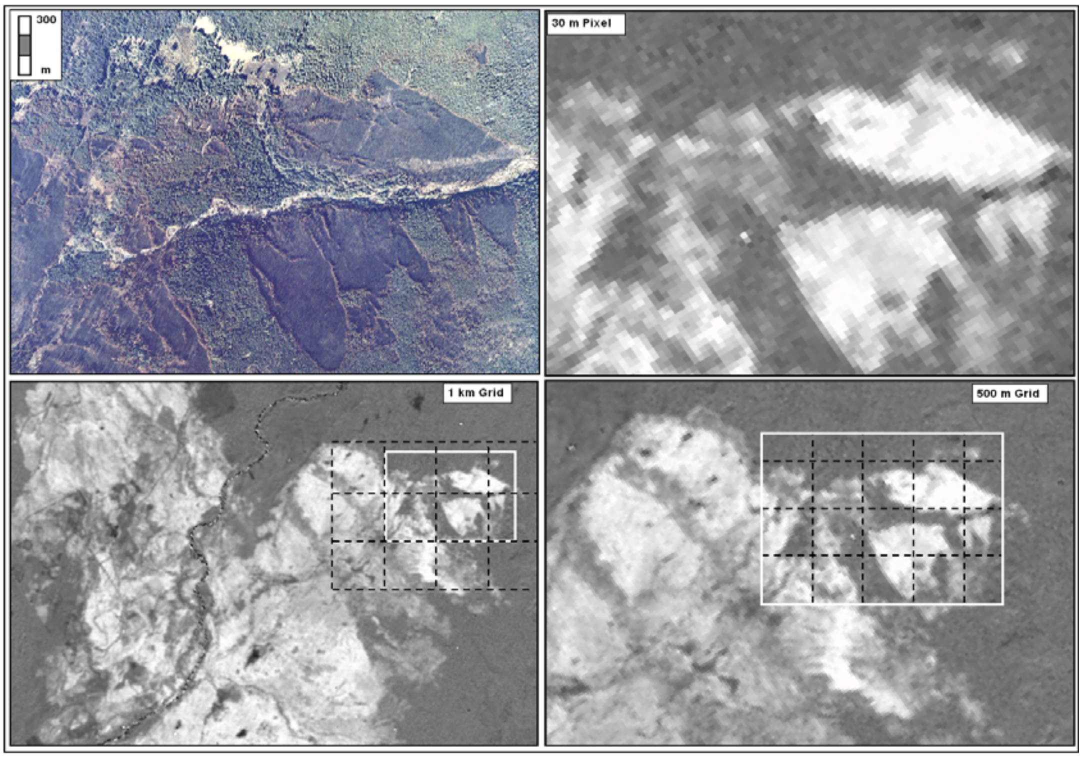
Beta variation impacts the ability to define ecologically important burn characteristics, such as edge, mosaic complexity (the variety and distribution of patches), and the overall range of responses (Slocum *et al.*, 2003; Beaty and Taylor, 2001; Weir *et al.*, 2000; Chen, 1999). Other affected attributes include derived sizes of burns and area of sub-units, e.g. distinct burn classes, watersheds or affected ecotypes (Nelson, 2005; Soja *et al.*, 2004).

A color aerial photo taken soon after fire shows sharp boundaries for larger patches of crown fire, and degrees of crown scorch down to individual trees (Figure 3 upper left). Very small patches and much spatial complexity are evident in the burn mosaic. Remaining in Figure 3 are subsets of a 30-meter dNBR, based on post-fire Landsat TM from about 10 months after fire. The grayscale corresponds to a linear gradient of change in NBR, with zero or no change being the medium gray lying mostly outside the burn. Higher positive and negative values are increasingly lighter and darker tones, respectively. Both represent degrees of departure from the neutral unburned condition, and relate to effects caused by fire when within the burn perimeter. More highly positive dNBR corresponds basically to increased charred surface and decreased green vegetation compared to pre-fire. The more negative the dNBR, the more fire enhanced plant growth over pre-fire conditions (McCarron and Knapp, 2003), visible as small dark patches of herbaceous vegetation on moist sites.

Impact to beta variation is evident between the aerial photo and the dNBR pixel matrix (upper right). At 30 m, minimum patch size increases, edges are less distinct, and thin linear features disappear, adding to the alpha variation captured by individual pixels. General shape and distinction of larger patches, however, are preserved. The mosaic retains at least the range and distribution of beta severity depicted in the aerial photo, with roughly one-to-one correspondence between larger patches. At 30 m, alpha variation is generally less than variation found between stands of ecological communities or between distinct burn patches. As a result, 30 m tends to suitably capture beta variation for whole-burn coverage and landscape perspectives in a single contiguous dataset (lower left). The level of generalization fits many applications, and is more efficient in practice than higher resolutions, especially for areas exceeding ca. 5000 ha.

As resolution decreases to 500 m and 1 km, burn heterogeneity incrementally decreases as attributes of beta-severity get incorporated into the alpha variation of grid cells (Figure 3 below). Portions of multiple dissimilar patches become aggregated, small patches consolidate with surroundings, and very few patches remain intact or distinctly represented by pure cells. The averaging reduces the potential range of values, greatly decreases the contrast of distinct edges, and impacts the ability to monitor small habitats, like meadows and wetlands. Thus, definition of alpha severity broadens to encompass between-stand characteristics and the diversity of burn patches (e.g. number, types, and proportions of multiple distinct patches). Such sensitivity is a function of fire-created patchiness, where in most ecotypes, natural spatial variation in fire behavior and effect is more fine scale than can be modeled at increments of 500 to 1000 m (Nelson, 2005; Price, 2003; Romme, 1982; Soja *et al.*, 2004). Remote sensing at lower resolutions would be most suitable for sub-continent to global scales, where cruder estimates would suffice for totaling up burned areas, emphasizing regional summary of all burns, and not beta variation within individual burns.

Figure 3. A complex burn pattern viewed at different scales (top left 0.3-1 m resolution; others 30 m). Grids reference beta variation pooled into pixels at lower resolutions. Coverage is about one third of the 13,780 ha burn.



4 TEMPORAL SENSITIVITY

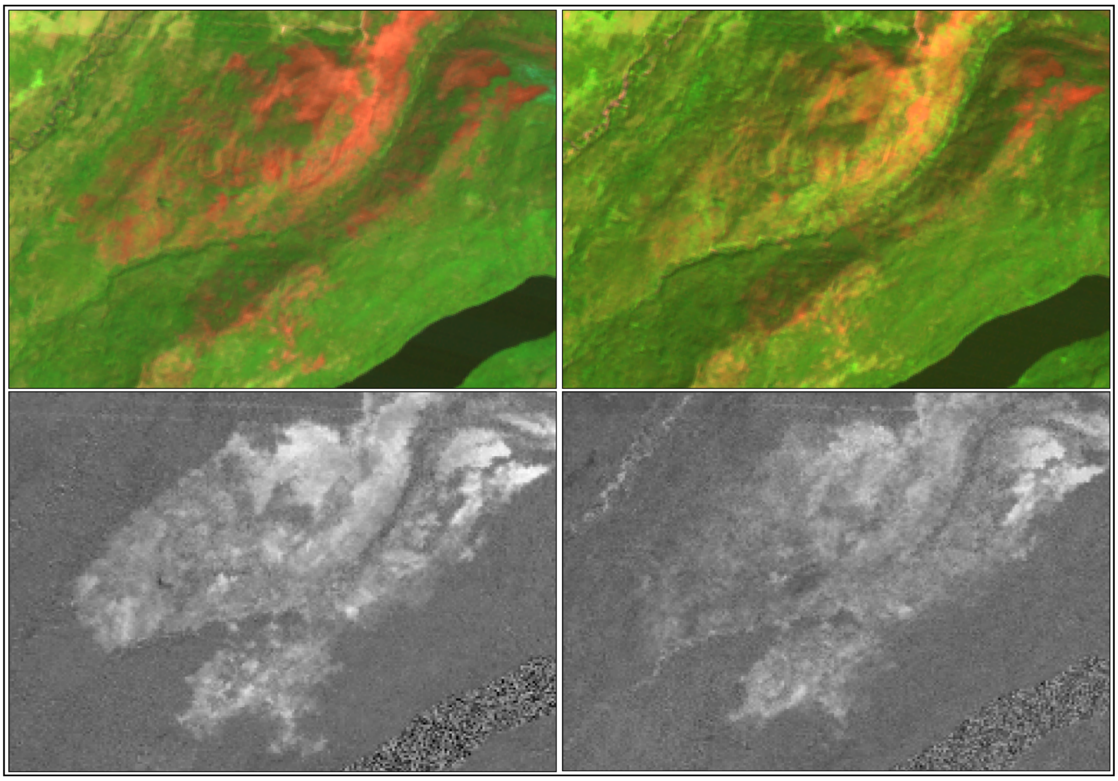
Temporal sensitivity of remote sensing to fire severity and recovery (Table 2) can be partitioned into interrelated factors concerning the time of year (*seasonal timing*), time since fire (*lag timing*), and the sampling return interval. The most universally influential are the first two, and will be emphasized below.

4.1 *Seasonal timing*

Seasonal timing relates to the time of year of image acquisition. It can detract from fire assessment when remote sensing closely follows the fire season, which is often a dry period, and in many temperate regions, during months distant from the summer solstice. Other factors aside, generally better contrast and a broader range of severity can be detected when unburned vegetation is relatively green and productive (Figure 4). Unburned vegetation that is green contrasts most with burned vegetation, especially when effects include light scorching or mottled burn patterns. Conversely, late-season dNBR can show less contrast within the burn and less distinction between burned and unburned areas; partly a radiometric response where naturally senescent and dry vegetation can mimic fire scorch or girdle. Snow cover is also a factor in mountainous regions for both early- and late-season acquisitions. If fire spans a large elevation range, it may be necessary to process two post-fire datasets, in order to capture the best time for phenology and snow in low and high elevation areas, respectively.

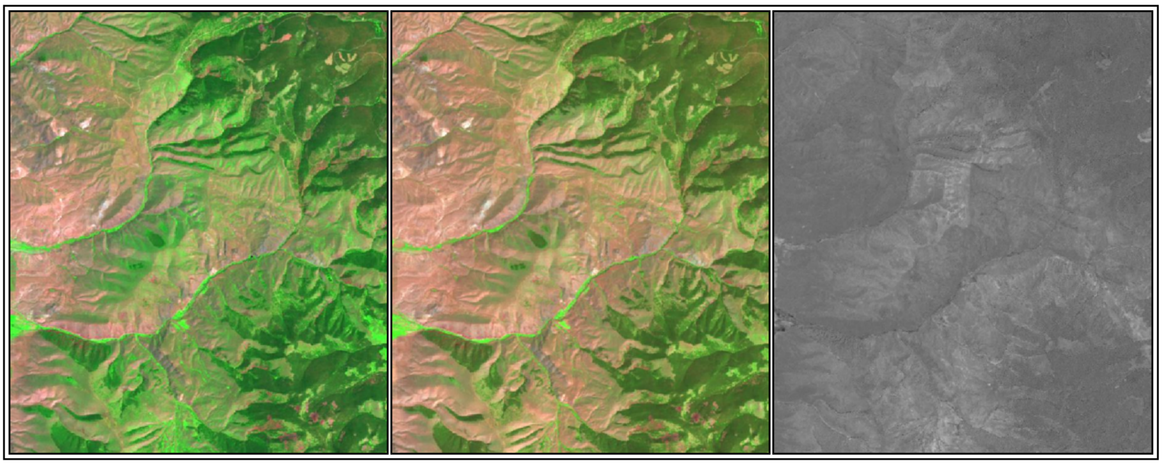
A compounding influence of seasonality is low sun angle that accompanies early- and late-season acquisitions (Miura *et al.* 2001). Generally, poor illumination and increased shadow, even on relatively flat terrain occupied by tall vegetation, decreases the definition of fire effects and sharpness of burn images (Figure 7 left). Low reflectance effectively degrades burned and unburned qualities, and dark shadow eliminates large areas from analysis (appearing speckled with high and low dNBR values). By contrast, images at Figure 7 right are much more distinct, enhanced by the better illumination near summer solstice, even on slopes facing away from the sun. A diagnostic characteristic is the narrower range and more uniform values of dNBR in unburned areas (lower right), which benefits burn discrimination.

Figure 4. Top, post-fire Landsat TM band 7,4,3 RGB composites; bottom, derived dNBR. Images left are during the growing season, 28 May 1995; and right, from near-end of growth, 1 Sept. 1995. The fire occurred in August 1994.



Seasonal timing is most relevant to multi-temporal analysis, or when several burns are compared using datasets from different times. To isolate change only due to fire, and to minimize affects from other processes that might appear similar, multi-temporal datasets should represent similar environmental conditions outside the burn. In regions with predictable seasonality, that can be achieved by choosing images from near the same time of year. When pre- and post-fire datasets are properly paired for sun angle and phenology, unburned areas appear similar to Figure 7 right. Unburned areas have similar gray tone, show little beta variation, and differenced-values are near zero. A large-sample frequency distribution of dNBR unburned pixels, used to test phenological correspondence between scenes, tends to be normally distributed with a mean dNBR < ±10 and standard deviation ca. < 50, on a scale of –2000 to +2000.

Figure 5. Mismatched phenology between multi-temporal datasets is evident in this unburned subset. The dNBR, right, derived from Landsat TM 16 July 1998, left, and ETM+ 1 August 2001, center.



Results are diagnostic if pre- and post-fire datasets are not suitably matched (Figure 5). The dNBR shows higher (lighter) values where pre-fire conditions, left, are evidently more productive and greener than the post-fire, center. (Oppositely, lower dNBR results when the post-fire state is greener.) However, none of the area burned; so detected change in NBR is not due to fire but rather natural phenological difference between acquisitions. The undesirable result lessens the distinction between burned and unburned, and creates false positives for fire effects when near or within burn perimeters. Severity levels of burned pixels are also biased. When scenes are not suitably matched, large samples of dNBR unburned pixels may not be normally distributed, and tend to have means ca. > ±15, on a scale of –2000 to +2000.

Bias in the unburned mean represents the average phenological difference between acquisitions, when other known causes of change are avoided in sampling. If beta variation within unburned is spatially uniform (unlike Figure 5), the biased distribution is approximately normal with a standard deviation ca. < 50. The entire dNBR dataset, then, can be offset by the bias, so that the adjusted unburned distribution has a mean of zero. This can be used in those cases to calibrate one dNBR to another.

Figure 5, however, depicts fairly high beta variation throughout the unburned dNBR, even though the paired dates are similar. Such temporal and spatial disparity in phenology is difficult to normalize without properly matched scenes. Unburned dNBR is less likely to be normally distributed, with typically larger bias and standard deviation than the previous example. It may occur in alpine or dry ecotypes, including herb and shrub communities that are moisture or snow limited (Grau and Veblen, 2000). Growth can vary dramatically year-to-year depending on stochastic weather; so multi-temporal scenes can be challenging to match. Distribution and intensity of green foliage and snow are the key factors, not simply time of year.

4.2 *Lag timing (time since fire)*

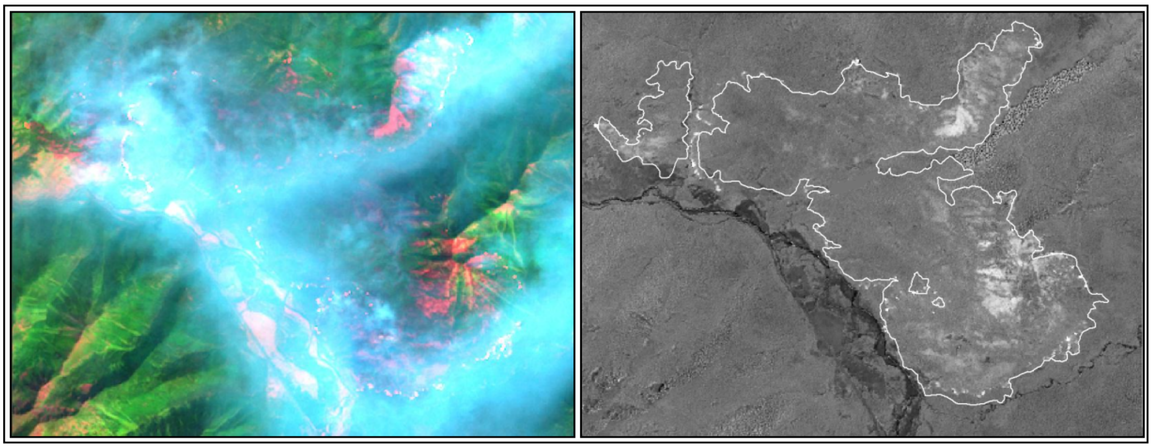
Post-fire assessments are meant to determine the actual ecological impact of fire, building from and perhaps correcting information collected at the time of active burning. In addition, they document the many fires that do not have any incident data. The key objective for many applications, including recovery, is to capture the spatial distribution of short-term severity. The quantity and quality of severity, however, is very much linked to the lag time when measurement occurs (Figure 1). In practice, three sampling intervals for remote sensing are identified here as *rapid, initial,* and *extended assessment*. Each has slightly different information content and constraints on quality and function (Table 3).

Table 3. Characteristics of different burn severity assessment types based on lag time after fire. For information content, P signifies perimeter and S severity.

Constraints	**Rapid**	**Initial**	**Extended**
Time Since Burn	< 2 Weeks	1 – 8 weeks	2 – 12 months
Burn Completion	Often burning	Most are complete	Complete
Fire Coverage	Larger, by request	Most > minimum size	All > minimum size
Data Availability	Limited	More	Most
Data Source	Multiple	Single	Single
Method	Variable	Single	Single
Information Content	P-, S-	P, S	P+, S+
Delayed Mortality	No	Minimal	Yes
Survivorship	No	Minimal	Yes
Phenology	Late	Late	Green
Transmittance	Variable	Little Better	Optimal
Sun Angle, Snow	Variable	Variable	Optimal
Quality Potential	variable	variable	best
Uses and Term of use	limited	more	permanent reference

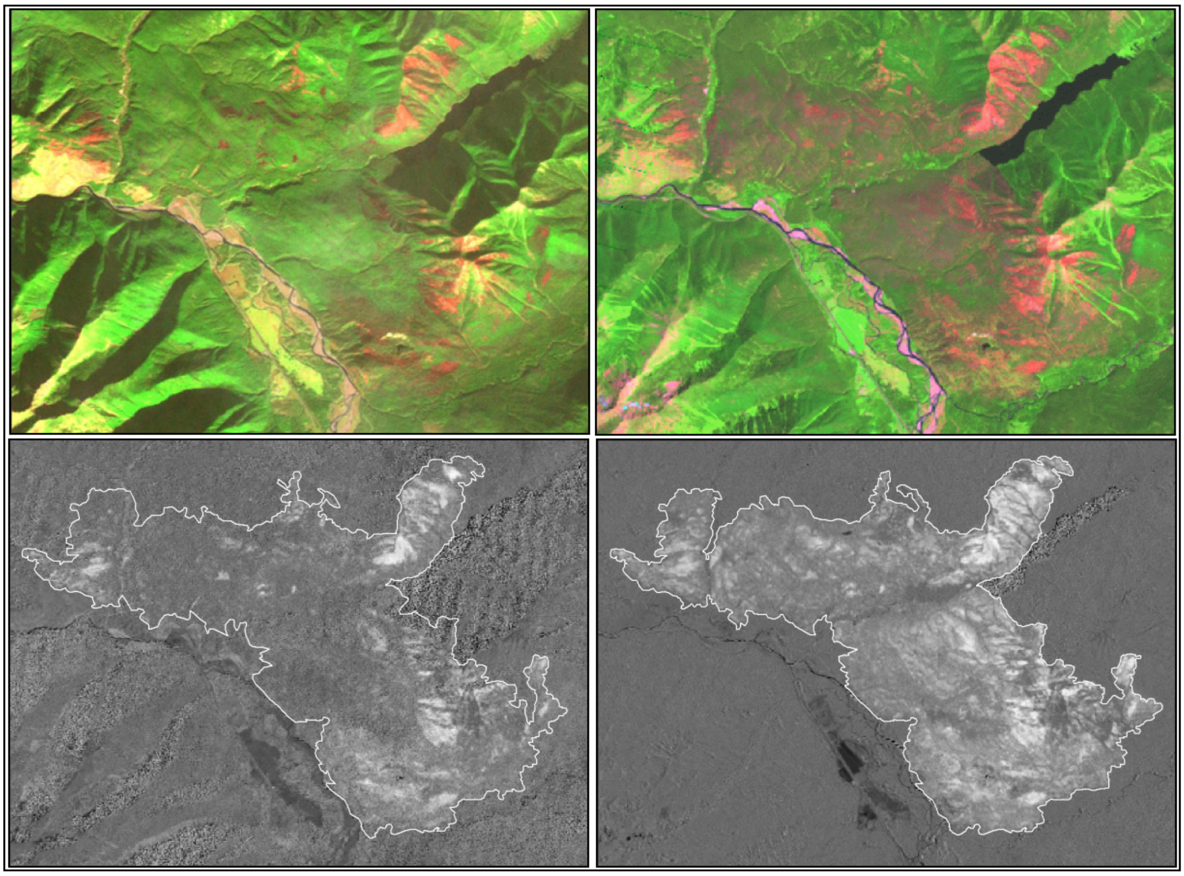
Rapid assessment (RA) is done almost exclusively for post-fire emergency response (USFS RSAC, 2005), and selectively on burns judged socio-economically important (Figure 6), typically larger fires affecting valued resources or assets. Since time is critical, planning and initiation of ground work dictate that remote sensing be completed within about two weeks of significant burning, often before the fire is completely out. In most cases, RA adequately serves to locate larger areas of high severity that constitute treatment priorities. Remote sensing data are often limited within the timeframe, however, and over many incidents; circumstances compel using a variety of approaches to offset the chance of getting no data. Where burning is complete, effects are raw and may not include some indicators such as vegetation survivorship or delayed mortality (Bond and Midgley, 2003; Abrahamson, 1984; Fowler and Sieg, 2004). Moreover, timing often comes when seasonal factors constrain the content and delineation of burn severity and perimeters, as discussed (Miura *et al.*, 2001), and results may record partial or incomplete effects. Thus over time, RA is less standardized, which, though necessary for the intended purpose, diminishes long-term utility. Also, for data quality and content concerns, the collective application of RA to research and long-term management is more limited. Some RA can be done with high-quality optimal data, but the variety of potential problems makes achieving consistently good results difficult.

Figure 6. RA with burn perimeter, post-fire 7 September 2003. dNBR, right, penetrates smoke to provide some information useful to emergency response; bright spots of active burning occur near perimeter. Compare to Figure 7.



Initial assessment (IA) is the first opportunity to get essentially complete ecological evaluation of a burn (Figure 7 left), initiated when 1) burning is essentially complete, and 2) sufficiently high quality data are available. Secondarily, it enables standard comparable data using one remote sensing approach across all burns, and targets any fire usually over some practical minimum size, with less restrictive coverage than RA. Flexibility exists to wait for high quality acquisitions and opportunity to compare multiple datasets. If reliable data is acquired within about two weeks of fire, and emergency planning is still in progress, the IA and RA are essentially the same, distinguished only by the data standards of IA. However, the wait for fire completion and quality data usually extends IA up to two months beyond the period for RA, which overall may improve atmospheric factors. But because a single sensor is used, it is still possible that suitable data may not be acquired despite the prolonged interval. In addition, IA is subject to the same limitations as RA when it comes to sun angle, phenology, delayed mortality and survivorship, with only minimal potential improvement in the latter (Kauffman and Martin, 1990). On the other hand, perimeters and severity may be more representative of the final state of the burn than RA.

Figure 7. IA, left, and EA, right, post fire scenes 25 Oct. 2003 and 15 July 2004, respectively. Change in detectable severity and perimeter is evident; also showing strong shadow and delayed mortality response. See RA in Figure 6.



Extended assessment (EA) occurs during the first growing season after fire (Figure 7 right). It captures first-order effects that include survivorship and delayed mortality of vegetation present before fire. The former is detected by regrowth from roots and stems of vegetation that burns but remains viable (McCarron and Knapp, 2003; Safford, 2004). It is indicative of effects that might appear severe a first, but do not result in sustained loss. Compared to IA, site severity is *diminished* by this process. The opposite is the case for delayed mortality (Fowler and Sieg, 2004; Agee, 2003; Rebertus *et al.*, 1989). It is detected from foliage that appears green and outwardly healthy soon after burning. Heating is insufficient to scorch or char much foliage, but effectively damages roots or cambium, and symptoms of necrosis develop over time. Conditions do not appear very severe at first, but actually result in lasting ecological changes on the site. Compared to IA, site severity is *increased* by this situation. Characteristically not recorded by RA or IA, survivorship and delayed mortality are, none the less, important indicators of the ecological change caused by fire and integral to defining and quantifying short-term site severity.

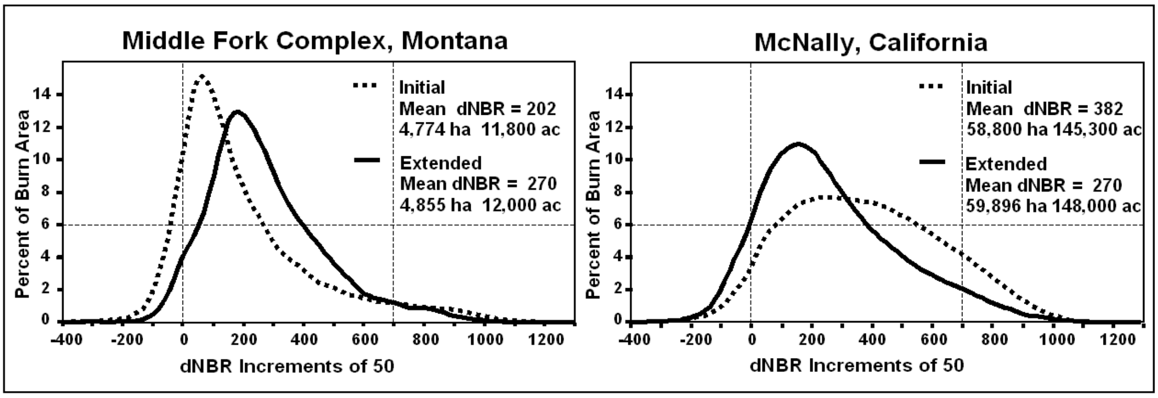
Most other first-order effects, such char, scorch and fuel consumption, are expected to persist until the next growing season, with two exceptions. Areas prone to surface erosion from wind or precipitation may show a decrease in ash cover and an increase of newly exposed mineral soil. Also, canopy foliage that is heat scorched or dies from girdling may drop to ground litter over the interval before EA. Since such effects are more or less complimentary in regards to severity assessment, these delayed responses are not expected to significantly alter the remotely sensed magnitude of change detected between IA and EA.

Lag time for EA varies depending on the climate and predominant ecotype (Abrahamson, 1984; Grau and Veblen, 2000; Kauffman and Martin, 1990; McCarron and Knapp, 2003; Fowler and Sieg, 2004). It can be as short as 1-3 months, where vegetation recovers very quickly after fire, as in grasslands, fire-adapted shrub communities, and diverse vegetation in moist warm climates lacking distinct seasonality (i.e. near-continual growth all year). Conversely, lag time can be 8-12 months post fire in many temperate and boreal regions with distinct seasonal growth. The interval typically brackets the summer solstice and can last for several months. Intermediate are drier moisture-dependent regions, where growth can occur at multiple or variable times of year. Thus, both IA and EA can be beneficial in some ecotypes, the former to identify what areas burned, and the latter to estimate the severity of first-order effects.

In any case, the time of year and length of time for EA usually translate into opportunity for more remote sensing data that is higher in radiometric quality than RA or IA. Sun angle, transmittance, snow and phenology are generally less problematic and more optimal for remote sensing. In addition, burning is complete, so the extent of perimeters and distribution of severity represents final conditions. Thus, the EA can provide more complete representation of actual effects. Generally all burns over a practical minimum size can be sampled with one standard remote sensing approach, so like IA, results can serve as permanent reference data to be used in long-term research and management.

In Figures 6-7, general improvement in data content and quality is clearly evident from RA until the time of EA, including final representation of the burn perimeter. The influence on severity for this burn is quantified by the dNBR histograms (Figure 8 left). The burn shows slight decrease in the frequency of very high values, due to small amount of regrowth, but fairly large shift in frequency from unburned and low severity values to more mid-range or moderate-severity values. The overall mean dNBR increases from 202 in IA to 270 in EA, indicating strong influence by delayed mortality between the two samplings. In this case, delayed mortality largely affected conifers burned by relatively low-intensity ground fire.

Figure 8. Paired IA and EA histograms showing within-burn contrasts in delayed mortality and survivorship.



In contrast, Figure 8 right shows severity dynamics influenced strongly by survivorship between IA and EA. A consistent shift to lower values is evident, and mean dNBR decreases significantly in EA, indicating lower severity overall than initially estimated. The response in any given burn (or burn portion), however, depends on the specific fire behavior, pre-fire fuel and vegetation, as well as the weather that prevails during and after fire (McCarron and Knapp, 2003; Safford, 2004; Slocum *et al.*, 2003). Survivorship and delayed mortality may completely offset one another, but rarely is there not some quantifiable effect from one or the other. Thus, much variation in survivorship and delayed mortality is anticipated between burns, and the dNBR frequency histogram can help distinguish different burn types based on the response.

5 SUMMARY

Remote sensing sensitivities are spatial, temporal and radiometric in nature. There is some latitude in design to select sensitivities that fit objectives and provide a suitable degree of comparability. Spatial factors principally relate to resolution and scale, which determine the aggregation of fire effects within the pixel (*alpha variation*), and control the ability to detect response patchiness and distribution throughout a burn (*beta variation*). As the minimum sample unit expands, the distribution and diversity of effects become increasingly complex and variable within the unit. Alpha variation extracts increasingly more beta variation from the structure of the whole burn, with corresponding decrease in edge distinction. This is important if objectives call for documenting beta variation within whole burns, and less so when the intent is to combine broad ranges of response over all burns at small scales.

Temporal sensitivities pertain to time of year and the time since fire when remote sensing occurs. Seasonal timing can impact radiometric quality of data in terms of transmittance, sun angle, and the potential for enhanced contrast within burn areas. Results typically improve when remote sensing occurs near summer solstice, snow effects are minimized, illumination is highest, and phenology provides green and productive unburned vegetation that maximally contrasts with fire effects. Remote sensing can degrade during or soon after many fire seasons when incomplete burning, hazy conditions, low sun angles, or extended drought are more common. In any case, radiometric and seasonal qualities should be selected for optimal discrimination, and multi-temporal datasets should be matched to reliably isolate fire-specific responses. An IA that is delayed to get higher quality data from a particular sensor can ameliorate problems associated with RA in emergency response. An EA, done during the growing season after fire, however, may be the best interval for quality data. Moreover, lag time influences the detectable qualities of burn severity, most notable are first-order effects evident in survivorship and delayed mortality developing through the growing season after fire. The RA and IA likely miss these ecologically important indicators, resulting in either over- or under-estimating severity. Accordingly, EA may provide more valid and complete representation of severity, with broader potential application over the long term.

Severity and recovery represent complex ecological conditions and processes, with definitions shaped by remote sensing potential. Constraints on fire response detection and information content point out a need for compatibility between remote sensing objectives and approach. Moreover, different spatial and temporal sampling strategies should not be mixed indiscriminately, without understanding the implications. This is particularly true of studies that analyze multiple burns, or test different radiometric measures, since results may not be comparable due to factors unrelated to severity or recovery. Adapting to such sensitivities enhances the value of permanent records useful for research and long-term management.

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