Remote sensing for prediction of 1-year post-fire ecosystem condition

Suggested Running Head: Fractional Cover and Fire Effects

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Abstract

Appropriate use of satellite sensor data in predicting long-term (i.e. >1yr post-fire) ecological effects of wildland fires requires that we remotely measure surface properties that can be mechanistically related to ground measures of post-fire ecosystem condition. This study evaluates whether the physical fractional cover measures of char, green vegetation, and brown vegetation within a pixel are improved predictors of 1-yr post-fire field measures, when objectively compared to the Differenced Normalized Burn Ratio (ΔNBR). Spectral mixture analysis (SMA) was applied to Landsat 7 Enhanced Thematic Mapper (ETM+) imagery acquired immediately following the 2000 Jasper Fire, South Dakota, to estimate immediate post-fire cover fractions. ΔNBR was calculated both immediately and 1-year post fire. Field data were collected within 66 *Pinus ponderosa* 0.28 ha study sites, established across the range of apparent post-fire conditions, and included data on the condition of the understorey and overstorey components. The measure of immediate char cover fraction either equaled or outperformed all other immediate measures in predicting 1-yr post-fire effects. Application of ΔNBR only provided a significant increase in regression performance for predicting percentage live tree when applied to 1-yr post fire imagery, as might be expected since the imagery better represents vegetation canopy condition measured during fieldwork. Fractional brown vegetation cover was a poor predictor of all effects (r^2<0.30) and each remote measure produced only poor predictions of crown scorch (r^2<0.20). Although further research is clearly warranted to evaluate more fires where fire effects data are available several years post-fire, char and green vegetation fractions may be viable alternatives to ΔNBR and similar indices to predict longer-term post-fire ecological effects. This may especially be the case when the spectral bands specific to ΔNBR are not available or when burn severity products are needed in a timely manner by wildland fire managers, such as by Burned Area Emergency Rehabilitation (BAER) teams.

Keywords: sub-pixel, severity, intensity, ponderosa pine, Black Hills

Table of Contents Summary:

We compare and evaluate the applicability of immediate post-fire estimates of percentage char and vegetation fractions, in addition to ΔNBR derived from Landsat ETM+ imagery, to remotely assess 1-yr post-fire ecological effects. The char fraction is a versatile indicator of canopy and sub-canopy effects and longer-term effects related to fire intensity.

1. Introduction

The large-scale, and in many cases remote, nature of many wildfires has made analysis of Earth Observation imagery an important and widely applied tool for immediate and long-term assessment of fire effects on ecosystems (Morgan *et al.* 2001; Lentile *et al.* 2006). Appropriate use of such remote sensing tools and techniques in predicting these fire effects, such as vegetation recovery and successional processes, requires that we investigate the empirical, biophysical relationships between remotely-sensed measures of post-fire surface condition; such as changes in reflectance, surface temperature, or fractional cover; with field measures of ecosystem condition (Lentile *et al.* 2006; Key 2006). Definitions and assessments of post-fire ecosystem condition often use the word ‘severity’, which for this paper will be described as ‘burn severity’ and includes fire effects on both vegetation and soils (Lentile *et al.* 2006).

Recent research to remotely infer post-fire effects has predominately focused on using the Differenced Normalized Burn Ratio (ΔNBR: Key and Benson 2006) spectral index or variants thereof (Holden *et al.* 2005; Miller and Thode 2007), which effectively measure the relative degree of vegetation and soil/char cover between pre and post-fire conditions (Smith *et al.* 2005; Lentile *et al.* 2006). Within North American wildfires, these values have been evaluated predominantly against a field measure termed Composite Burn Index (CBI) (van Wagtendonk *et al.* 2004; Brewer *et al.* 2005; Cocke *et al.* 2005) with only limited studies evaluating regressions with specific biological/ecological measures of post-fire effects (e.g., Smith *et al.* 2007b; Hudak *et al.* in review). CBI is an integrative measure of post-fire effects across under- and overstorey strata. Numerous studies have highlighted limitations in both ΔNBR and CBI, namely:

(i) The CBI measure is commonly calculated in a subjective and qualitative manner with some evaluations conducted without explicit knowledge of pre-fire ecosystem condition (van Wagtendonk *et al.* 2004);

(ii) ΔNBR often exhibits non-linear asymptotic relationships with CBI (van Wagdentonk *et al.* 2004; Cocke *et al.* 2005; Wimberly and Reilly 2007), which further varies with both spatial scale (van Wagtendonk *et al.* 2004) and ecosystem type (Epting *et al.* 2005);

(iii) Contemporary studies have shown that the spectral bands used to calculate NBR are not optimal to evaluate the degree of burning (Smith *et al.* 2005; Roy *et al.* 2006);

(iv) ΔNBR has been shown to be sub-optimal in woodland and grassland environments (Epting *et al.* 2005; Roy *et al.* 2006; Miller and Thode 2007); and

(v) Roy *et al.* (2006) highlighted that the original application of the ΔNBR was for burned area mapping (Lopez-Garcia and Caselles, 1991), which relies on fundamentally opposite assumptions to methods used to assess a range of biophysical variation within an area (Verstraete and Pinty 1996; Roy *et al*. 2006), such as a range of "severity" after a wildfire.

Specifically in terms of (v), any land cover classification approach ideally seeks to produce class histograms with low internal variance, such that the different class histograms are less likely to overlap and therefore would exhibit higher separability (Verstraete and Pinty 1996; Pereira 1999). In contrast, when evaluating within-area effects (such as severity) a large dynamic range of within-class values are desired to provide detailed characterization of those effects. In essence the user needs individual class histograms to be very wide, or at least exhibit bi- or tri- modal properties, to enable splitting of any particular class into say distinct regimes, such as "low, moderate, and high”. As these are mutually exclusive objectives (Verstraete and Pinty 1996; Pereira 1999), ΔNBR and any other similar spectral index cannot be optimal for characterizing both burned area and post-fire effects related to severity (Roy *et al.* 2006). However, due to mixed results in the application of ΔNBR to severity assessments in a range of fire types outside the area for which it was originally developed (Key 2006), it remains unclear as to whether ΔNBR is most suited to the assessment of area burned or severity. However, whichever case is ultimately determined, it is clear that to optimize the assessment of area burned and severity, two separate methods are required: the first to identify the extent of area burned and the second to analyze the severity within that extent.

These factors potentially limit wide-scale applicability of ΔNBR to infer post-fire ecosystem condition and highlight the need for further research into alternative and more appropriate remote sensing methods (Roy *et al.* 2006). Recent research has highlighted spectral mixture analysis (SMA) as an alternative approach with potential to meet this need (Lentile *et al.* 2006; Smith *et al.* 2007a,b; Hudak *et al*. in review). SMA, which has been widely applied to produce maps of the area burned (Wessman *et al.* 1997; Cochrane and Souza 1998; Vafeidis and Drake 2005; Smith *et al.* 2007a), enables estimation of fractional cover of burned and unburned components contained within each pixel. The approach relies on the assumptions of linear spectral mixing models (Drake *et al.* 1999) and is thus inherently scalable across data of different spatial resolutions (Settle and Drake 1993). SMA also can be applied to any type of imagery with multiple channels in the visible and near-infrared wavelength regions, without reliance on the availability of specific channels (e.g., bands 4 & 7 to calculate ΔNBR from Landsat TM or ETM+). Furthermore, it allows production of measures that are directly analogous to traditional

U.S. Forest Service 'field severity' assessments of % green, % brown, and % black (Lentile *et al.* 2006). Smith *et al.* (2007b) observed in a recent preliminary study that in comparison to an immediate post-fire measure of ΔNBR, the estimate of fractional char cover applied to a mixture of aspen and ponderosa pine plots produced marginally improved predictions of 1-yr post-fire % live trees. Furthermore, Hudak *et al.* (in review) observed that green fractional cover was an equal or improved correlate to multiple post-fire effects when compared to an immediate post-fire measure of NBR, or ΔNBR. Therefore, following on from Smith *et al.* (2007b) and Hudak *et al.* (in review), the objectives of this study are:

(1) Evaluate whether SMA-derived estimates of fractional char, green, and brown vegetation covers are improved predictors, over immediate ΔNBR (NBR_{pre}-$NBR_{immediate}$), for a wide variety of both canopy and surface ecological indictors measured in 66 ponderosa pine plots 1-yr post-fire, and
(2) Evaluate whether these immediate fractional measures are improved correlates of 1-yr post-fire conditions when compared to ΔNBR calculated from pre- and 1-yr post-fire imagery (NBR_{pre}-$NBR_{1\text{-yr post fire}}$).

2. Methods

2.1 Study Area

This study focused on the Jasper Fire, which during 9 days in the summer of 2000 burned ~33,800 ha in the Black Hills of western South Dakota, USA. Within the fire, latitudes range from 43°41'35" to 43°55'48" N and longitudes range from 103°46'1" to 104°0'47" W. Elevations range from ~1500 to 2100 m. The Black Hills is an isolated mountain range on the Northern Great Plains physiographic province in western South Dakota and northeastern Wyoming (Figure 1). As the easternmost extension of the Rocky Mountains, the Black Hills were formed by regional uplift between ~35 to 65 several million years ago. This uplift produced an elliptical dome with an older crystalline core surrounded by younger, steeply dipping sedimentary deposits (Shepperd and Battaglia 2002). The Limestone Plateau surrounds the core and the area burned by the Jasper fire is located on the southwestern extent of this fertile plateau. The area within the Jasper fire perimeter is characterized by relatively continuous, ponderosa pine (P*inus ponderosa*) stands, although occasional quaking aspen (*Populus tremuloides* Michx.) clones and grasslands also exist. A complete description of the study area and fire regime is provided in Lentile (2004) and Lentile *et al*. (2005).

2.2 Remote Sensing Data and Methods

Three Landsat ETM+ images of the study area were acquired (18 August 1999; 14th September 2000; 24 September 2001). Each image was corrected to top-of–atmosphere reflectance using the standard Landsat 7 calibration equations (http://landsathandbook.gsfc.nasa.gov/handbook.html). Following Cocke *et al.* (2005), the Normalized Burn Ratio (NBR), defined as the normalized difference of Landsat bands 4 and 7: (TM4-TM7)/(TM4+TM7), was determined for each image. The ΔNBR was then calculated from both the immediate and 1-yr post-fire images. Rather than classifying ΔNBR values using arbitrary thresholds, we used the continuous ΔNBR values in subsequent regression analyses. Two forms of ΔNBR were applied, namely the 'immediate

ΔNBR', which used the pre-fire and immediate post-fire image, and the '1-yr post-fire ΔNBR', which as the name suggests used the pre-fire and 1-yr post-fire image in the ΔNBR calculation. Following Cocke *et al.* (2005), each ΔNBR image was then scaled by multiplying each value by 1000. For this analysis the immediate post-fire Landsat ETM+ imagery was additionally converted into ground-reflectance using the standard method of 'dark body subtraction' using the minimum band pixel values as selected by the ENVI software package (RSI, Boulder, CO).

The estimation of fractions of char (Figure 1), brown vegetation, and green vegetation within each Landsat pixel was determined using spectral mixture analysis (Settle and Drake 1993). Although non-linear spectral unmixing methods do exist and have been applied to fire affected surfaces (Smith *et al.* 2005), the complexity in their implementation lends to the widespread use of linear models (Drake *et al.* 1999; Chen *et al.* 2004). Importantly, the principal assumption of linear mixture models, namely that a mixture of 50% of A + 50% of B will have a spectral reflectance of [A+B]/2) over all analyzed wavelengths (0.3-2.5 μm), has been shown to be broadly valid when considering mixtures of unburned and burned surfaces (Cochrane and Souza 1998; Vafeidis and Drake 2005; Smith *et al.* 2005). The classical linear spectral unmixing model is defined by Drake *et al.* (1999) as:

$$R_i = \sum_{c=1}^{n} (r_j f_{ij}) + e_n \qquad (1)$$

Where, R_n is the reflectance for the i^{th} pixel, r_j is the spectral reflectance of the j^{th} surface component, f_{ij} is the fraction of the j^{th} surface component in the i^{th} pixel, and e_n denotes the pixel noise term.

Generic spectra of senesced vegetation, green vegetation, and char (Figure 2) were used as several past studies have remarked that these spectral reflectance curves are broadly similar across a wide range of different environments (Elvidge 1990; Landmann 2003; Smith *et al.* 2005, 2007a,b Hudak *et al*. (in review)). Linear spectral unmixing was applied using the IDL/ENVI ver 4.2 module with the ‘sum to 1’ constraint applied (Drake *et al*. 1999), which ensures that all component fractions within a pixel add up to unity, although individual class fractions may be negative or exceed 1. Each ΔNBR and fractional cover estimate was then extracted at each plot location using the ARC software package (ESRI, Redlands, CA, USA).

2.3 Field Measurements

In April 2001, as part of Lentile (2004), three ~800 ha study areas were identified that contained a mosaic of fire effects in the north, central, and southern portions within the Jasper fire perimeter. Management activities were limited to roadside hazard tree removal and spot spraying of noxious weeds in study areas. Sites were selected in areas of low, moderate, and high burn severity, expressed in terms of post-wildfire appearance of vegetation, litter, and soil. Sixty-six 0.28 ha sites were established in burned pine forests and 9 unburned pine stands were selected to provide a surrogate for pre-fire conditions. Sites were similar with respect to species composition, aspect, slope (5-13%), elevation, and soil type.

Twenty meters from each site center at 0°, 135°, and 225° bearings, three 0.03 ha plots were established. On these plots, data on the fire effects on the canopy, boles, and around the bases of individual trees > 5 cm diameter breast height (dbh) were collected. The minimum and maximum heights of crown scorch and crown consumption on individual trees were recorded. The portion of the crown scorched or consumed within this area was visually estimated to the nearest 5%, allowing the percent of crown scorched or consumed relative to the entire live crown length to be calculated. The maximum height of bole scorch and the percent of the bole affected by scorch relative to total tree height were also measured and calculated, respectively. Basal scorch and basal char were assessed as the percent of the bole circumference either scorched or charred at heights less than 30 cm. Scorched bark was intact and gray-black in color, with distinguishable furrows and a flaky texture. Charred bark was often partially eroded by fire and metallic black in color, with undistinguishable furrows, and charcoal-like texture. Figure 3 depicts a typical ponderosa pine stand1-yr following the Jasper fire.

Following Ryan and Noste (1985), the percent low, moderate, and/or high ground char in a one-meter radius area around the base of each tree was measured, as were bark depths at two points on each tree. Line transects (30 m) were laid at 90° and 270° bearings with the site center as the midpoint. Depths of forest floor litter/duff and the percent low, moderate, and/or high ground char (Ryan and Noste 1985) for a 0.025 m^2 surface area were measured at 30 points at 2 m intervals along these transects. An index of burn severity (BI) was defined as a weighted sum of the product of the proportion of the ground area charred with the degree of char scaled from low (1) to high (3). Within each of the subplots (or individual) tree plots, we characterized the forest floor/ ground/ soil effects. As these measurements were not originally intended for the purposes of a char or remote sensing analysis, we assigned a proportion low, moderate, and high burn severity based on widely applied descriptions of field severity (Ryan and Noste, 1985). To calculate the Burn Index, we multiplied the % low times 100; the % moderate times 200; and the % high times 300; and then summed these scores. BI was calculated within a 1 m radius area around the base of each tree within plots (Total BI 1 m tree), and for each of the 30 forest floor points located at 2 m intervals along the transect (Floor BI). At six additional points offset from the transect, samples were collected, and later oven-dried and weighed to estimate forest floor biomass.

3. Results

3.1 General Description of Post-Fire Effects

The direct and cumulative effects of fire on pine trees were much greater on high severity than on low or moderate severity sites. Approximately 1, 22, and 100% tree mortality was found in pine stands. The entire bole was scorched, and canopy foliage and small branches were completely consumed in areas of high-severity fire. Bole and crown scorch was more extensive on moderate than on low severity sites. Approximately 75% of the crown was scorched or consumed on moderate severity as compared to ~20% on low severity sites. On average 80% of the base of each tree bole was scorched on low and moderate severity sites, and 2.2 times more char was found on the base of each tree on moderate severity sites relative to low severity sites. Post-fire bark thickness (SE) was 1.5 (0.1), 1.2 (0.1), and 0.7 (0.1) cm in low, moderate, and high severity sites.

Fire effects on the forest floor were most substantial in areas of high burn severity where litter and duff were almost completely consumed. Floor BI was 119 on low, 186 on moderate, and 246 on high severity sites on a BI scale of 100 to 300. Average litter depths (SE) were 1.2 (0.3), 0.5 (0.2), and 0.2 (0.1) cm on low, moderate, and high severity compared with 4.8 (0.5) cm on unburned sites. Fire reduced litter depths by ~ 76, 91, and 97% on low, moderate, and high severity sites one year post-fire. On average, there was 2.3 and 6.6 times more duff on unburned sites than on low and moderate sites. No duff remained on high severity sites. Litter organic weights (SE) were 1266.4 (263.8), 683.5 (172.7), 458.6 (92.6), and 82.1 (45.4) gm^{-2} in unburned, low, moderate, and high severity sites.

3.2 Prediction of 1-yr Post-Fire Effects

The results of the regression predictions are presented in Tables 2a and 2b. Apart from the relation between 1-yr post-fire ΔNBR and percentage live tree (r^2=0.74), fractional char cover either equaled or outperformed all other remote measures, whether immediately or 1-yr post-fire. Each remote measure produced poor predictions of crown scorch, with the char fraction and ΔNBR methods having significant but poor relationships (r^2<0.17, p<0.031). The results illustrate that fractional char cover is a reasonable predictor of several canopy and sub canopy measures (Table 2a,b). In terms of canopy measures, fractional char cover produced reasonable predictions of percent live trees (r^2=0.69) and % crown consumption (r^2=0.65), and was comparable to the results obtained using the 1-yr post-fire ΔNBR measure. However, the improved performance of the 1-yr post-fire ΔNBR measure might be expected since both the imagery and field measures are effectively coincident measures of the same condition. In terms of sub-canopy measures, fractional char cover strongly predicted % bole scorch (r^2=0.72) and weight of organic litter (r^2=0.71), while fractional green cover produced weaker but reasonable predictions (r^2=0.60 and r^2=0.64 respectively). Both the char and green cover fraction predictions surpassed the immediate post-fire ΔNBR predictions of these 1-yr post fire effects.

Immediate ΔNBR was shown to be a reasonable predictor of % live trees (r^2=0.53), % bole scorch (r^2=0.50), and weight of organic litter (r^2=0.59). Furthermore, although 1-yr post-fire ΔNBR outperformed immediate post-fire ΔNBR for most of the post-fire effects, the immediate measure did produce a marginally improved prediction, in terms of the coefficient of determination, of the depth of the 1-yr post-fire litter. Again, these general results of higher coefficient of determination in using the 1-yr post –fire ΔNBR would be expected as this index incorporates data that is effectively coincident with the 1-yr post-fire field measures.

4. Discussion

4.1 Remote prediction of post-fire effects

To predict implies to 'forecast a situation that is yet to occur'. Therefore, it is not appropriate to predict field measures of post-fire effects with 1-yr post-fire ΔNBR, as this is effectively measured concurrently with the 1-yr post-fire field measures. Applications of 1-yr post-fire data can lead only to a prediction if they are regressed on field data collected at an even later date (e.g. 2-, 5, or 10-years post-fire). Thus, the regressions herein were presented solely for the purpose of determining the 'potential inference ability' of the 1-yr post-fire ΔNBR (Table 2a,b).

Timely prediction of field-based ecological indicators of 1-yr post-fire effects must instead be achieved through the use of methods measured either before or immediately following the fire event, as it is not practical to wait a year before making a 1-yr post-fire prediction.

These results demonstrate that immediate ΔNBR is a poorer predictor of 1-yr post-fire ecological indicators than char cover fraction, and also in most cases, green cover fraction. The ability of immediate ΔNBR to reasonably predict 1-yr post-fire % live crown is because the index is sensitive to the quantity of green and senesced vegetation (governed by Landsat band 4) and, to a lesser extent, the quantity of exposed soil or char cover (governed by Landsat band 7) present within the immediate post-fire pixel (Eva and Lambin 1998a,b; Stroppiana et al 2002; Smith *et al.* 2005; Lentile *et al.* 2006; Key 2006). In instances where either the canopy component is relatively untouched or completely consumed (e.g., in a stand replacing fire), the 1-yr post-fire canopy conditions may still represent the same relative amount of green vegetation. In contrast, the understorey immediately following the fire will be dominated by char and mineral ash, which 1-year later will have been removed by wind and water processes or occluded by vegetation regrowth or scorched needlecast (Smith and Hudak 2005). As such, the contribution of band 7 to the ΔNBR might simply be adding noise to the predictions of the sub-canopy ecological indicators. These effects would be less pronounced where canopy closure remains high (unburned or low degree of fire effects) or in stand replacing fires where the understorey could be replaced by bare soil. The unexpected ability of the immediate ΔNBR to predict the understorey 1-yr post fire measure of organic litter weight could potentially be an indirect effect of the combined impact of scorched canopies with extensive surface fires. In such fires, although we would expect the surface material to be consumed, scorched needles would fall to produce new litter for the 1-year post-fire measurement. In contrast, low severity fires and stand-replacing fires abundant and little organic litter weights would be expected respectively.

These results illustrate that measures of both the immediate post fire char and green vegetation fractions are good predictors of several 1-yr post-fire canopy and several sub-canopy measures. Most notable, several of these 1-yr post-fire measures appear to be potential surrogates of fire intensity. Specifically, the % bole scorch can be considered a proxy to the flame length, while the average bark thickness, scorch to 1m, and organic litter weight might each relate to the rate of spread, or the duration of fire at a point. Therefore, these fractional measures have the potential to inform managers regarding tree mortality (via canopy condition and average bark thickness), and provide viable proxies of fire intensity to Burned Area Emergency Rehabilitation (BAER) teams tasked with deciding where post-fire mitigation efforts are needed.

4.2 Linking post-fire effects to the carbon and water cycles

The ecological field indicators of post-fire effects measured in the field typically reflect fine-scale processes, but also impact coarse spatial (regional) and temporal (decadal) scales. For such measures to be applicable in describing ecosystem recovery and condition across a range of scales and ecosystems, they should physically relate to pools and fluxes of biophysical variables (e.g. the carbon and water cycles). Although the mechanistic relations between fire effects and the carbon and water cycles are not currently well defined, the results of this study support the argument that measures of the fractional cover are potentially versatile measures of the post-fire ecological impact that also have direct and tangible consequences on the terrestrial carbon and water cycles (Table 3).

4.3 Management Implications

The practical application of this ecological information addresses two main points. First of all, our research suggests that immediate post-fire assessments, particularly those that utilize only immediate post-fire dNBR techniques, can be misleading. The post-fire environment will change greatly within one year, some aspects of which may be predictable while others may be related to local and regional climate. Char fractional cover may be a viable alternative to ΔNBR to predict longer-term post-fire ecological effects, especially when the prediction is needed in a timely manner, e.g., BAER teams must make treatment recommendations within 7 days following fire containment. Secondly, post-fire recovery generally is more rapid in less severely burned areas; however, commonly applied ΔNBR techniques provide very little information about the effects of fire on the forest floor and soil. As such, the char fraction is particularly useful in fire regimes where some, but not all, of the canopy is consumed. The mosaic of relatively small patches of severely burned forests interspersed within less severely burned forests, a common signature of surface and mixed-severity fire regimes, exerts a strong influence on post-fire landscape heterogeneity and rates of recovery. In some extensive areas of high-severity fire, post-fire vegetation dynamics may not follow the same trajectory as less severely burned areas, and a cover type conversion from forests to shrubs or meadows may occur.

From a management perspective, streamlined assessment of fire effects on overstorey, understorey, and forest floor communities can be used to predict areas likely to develop vegetation structure different from pre-fire conditions, and will facilitate post-fire monitoring and mitigation (Lentile *et al.* in review). Identification of desirable attributes of fire behavior and positive post-fire effects may improve restoration strategies. For example, recognition of initial fire effects likely to result in tree death may facilitate selection of which trees to salvage harvest or leave as potential seed sources. In some burned areas, reforestation or seeding are probably unnecessary and could interfere with natural successional dynamics. Furthermore, severely burned areas with low rates of recovery may indicate areas that require immediate attention or are highly vulnerable to displacement of native flora by invasive species. If a cover type conversion from ponderosa pine to shrub-dominated communities is desirable for wildlife habitat diversity, then large patches of high severity may lend themselves to this objective. Longer interval, large-scale fire events, such as the Jasper fire, may be critical in maintaining landscape heterogeneity and diversity. Openings in a previously dense, closed-canopy forest may represent a desirable departure from pre-fire conditions and a return of some attributes of historical landscape function. Rapid landscape characterization that can be mechanistically related to ground measures of the post-fire ecosystem condition may provide much needed management guidance and decision support following such large fire events.

5. Conclusions

The principal limitation of the current study is that it is only a preliminary study that represents information from a single wildfire. Further research is clearly warranted to repeat the fractional cover methodology and comparable fieldwork analysis on data from several other large North-American wildfires to determine whether the predictive relationships identified herein are transferable to other fire regimes. Further research is clearly also warranted to repeat this methodology on data collected from fires 5, 10, or even 20 years post-fire, to evaluate the capability of such immediate post-fire remote sensing data to predict very long-term ecological responses to fire, such as succession processes and carbon accumulation. Such data may be feasible via analysis of widely researched historical fires such as those that occurred in Yellowstone National Park in 1988.

Acknowledgements

This fieldwork component of this study was funded by the Black Hills National Forest through In Service Agreement No. 0203-01-007, Monitoring Fire Effects and Vegetation Recovery on the Jasper Fire, Black Hills National Forest, South Dakota to Rocky Mountain Research Station and Colorado State University. The subsequent research was supported in part by funds provided by the USSA/USDI Joint Fire Sciences Program (Projects 03-2-1-02 and 05-4-1-07). Alistair Smith is part of the ForestPARC, which is funded by the Upper Midwest Aerospace Consortium, with funding from NASA.

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Table 1. Direct fire effects measured on the boles and in crowns of trees after the Jasper fire. All values are mean ± standard error. * denotes significance ($P < 0.05$)

Burn Severity	**Crown Scorch (%)**	**Crown Consumption (%)**	**Bole Scorch (%)**	**Basal Scorch (%)**	**Basal Char (%)**	**Bole Scorch at 1 m (%)**
Low	19.5 (3.3)	0.1 (0.1)	15.2 (2.1)	80.2 (4.1)	8.7 (3.6)	35.3 (7.6)
Moderate	69.7 (4.3)	4.9 (2.2)	41.9 (3.2)	79.3 (6.2)	19.2 (6.2)	87.1 (2.6)
High	8.8 (7.3)	90.6 (7.3)	99.7 (0.2)	48.2 (9.3)	51.8 (9.3)	99.9 (0.1)
P	0.0001 *	0.0001 *	0.0001 *	0.0001 *	0.0001 *	0.0001 *

Table 2. Prediction results between remote sensing and fractional cover measures ** Denotes not significance at the 95% level and SE denotes the standard error of the estimate.

2a.) Prediction statistics (n=66) between immediate post-fire remote fractional measures (char fraction, green vegetation fraction) with 1-yr post-fire field measures.

	Remote Measures (x)					
	Fraction Char Cover			Fraction Green Cover		
Ground Predictor (y)	r^2	SE	Equation	r^2	SE	Equation
Canopy variables						
% Live Tree	0.69	23.17	-483*x+487	0.59	25.65	254*x-15
Crown Scorch	0.17	31.73	-201*x+224	**		
Crown Consumption	0.65	26.25	499*x-422	0.42	33.83	-227*x+89
Total Fire Crown Effects	0.57	18.88	298*x-197	0.55	19.16	-168*x+114
Sub-Canopy variables						
Bole Scorch	0.72	18.27	411*x-318	0.60	22.12	-212*x+108
Basal Charring	0.33	28.77	277*x-206	0.32	28.82	-157*x+84
Basal Scorch	0.21	4.81	35*x+65	0.16	4.97	-17*x+101
Average Bark Thickness	0.48	0.28	-3.6*x+4.3	0.35	0.32	1.8*x+0.51
Scorch 1m	0.43	20.29	243*x-144	0.44	20.02	-141*x+112
Total BI 1m tree	0.64	36.96	289*x-396	0.56	41.12	-365*x+320
Floor BI	0.44	49.37	607*x-339	0.31	55.04	-277*x+284
Litter Depth	0.49	0.24	-3.4*x+3.5	0.39	0.27	1.7*x+0.04
Litter Organic Weight	0.71	3.99	-80*x+82	0.64	4.40	44*x-1.70

Table 2b. Prediction statistics (n=66) between immediate and 1-yr post-fire ΔNBR with 1-yr post-fire field measures.

	Remote Measures (x)					
	Immediate ΔNBR			1-yr Post ΔNBR		
Ground Predictor (y)	r^2	SE	Equation	r^2	SE	Equation
Canopy variables						
% Live Tree	0.53	28.65	-0.102*x+105	0.74	21.24	-0.125*x+97
Crown Scorch	0.07	33.58	-0.031*x+58	0.16	31.98	-0.048*x+61
Crown Consumption	0.44	33.46	0.098*x-23	0.62	27.42	0.122*x-16
Total Fire Crown Effects	0.49	20.51	-0.067*x+35	0.55	19.27	0.074*x+44
Sub-Canopy variables						
Bole Scorch	0.50	24.50	0.083*x+10	0.68	19.58	0.1*x+17
Basal Charring	0.28	29.77	0.062*x+11	0.34	28.36	0.072*x+18
Basal Scorch	0.19	4.88	0.008*x+93	0.22	4.78	0.009*x+94
Average Bark Thickness	0.43	0.30	-0.001*x+1	0.48	0.28	-0.001*x+1.30
Scorch 1m	0.31	22.37	0.050*x+50	0.43	20.17	0.062-x+56
Total BI 1m tree	0.53	42.46	0.151*x+146	0.63	37.48	0.171*x+164
Floor BI	0.40	51.29	0.140*x+132	0.50	46.73	0.163*x+148
Litter Depth	0.42	0.26	-0.001*x+1	0.36	0.28	-0.001*x+0.74
Litter Organic Weight	0.59	4.71	-0.018*x+19	0.63	4.47	-0.020*x+16

Table 3. Relation between % cover measures of burn severity and carbon (C) and water (H_2O) cycles. ET denotes evapotranspiration.

Ecological Metrics	Fire-Effects Reference(s)	Linkages to C and H_2O Cycles
Tree survival/mortality	Miller and Yool (2002)	C accumulation/ET rates
	Litton et al (2003), Trumbore (2006)	
Bare soil	Gosfoth et al (2005)	Plant establishment/Soil respiration rates
Reddened soil	Doerr and Cerda (2005)	Infiltration, water repellency, and erosion
Exposed litter	Lewis et al (2006)	Plant establishment/water repellency
	Crockford and Richardson (2000)	Surface evaporation
White ash	Smith et al (2005b)	C volatilization/water repellency
Coarse woody debris	Smith and Hudak (2005)	C volatilization/erosion

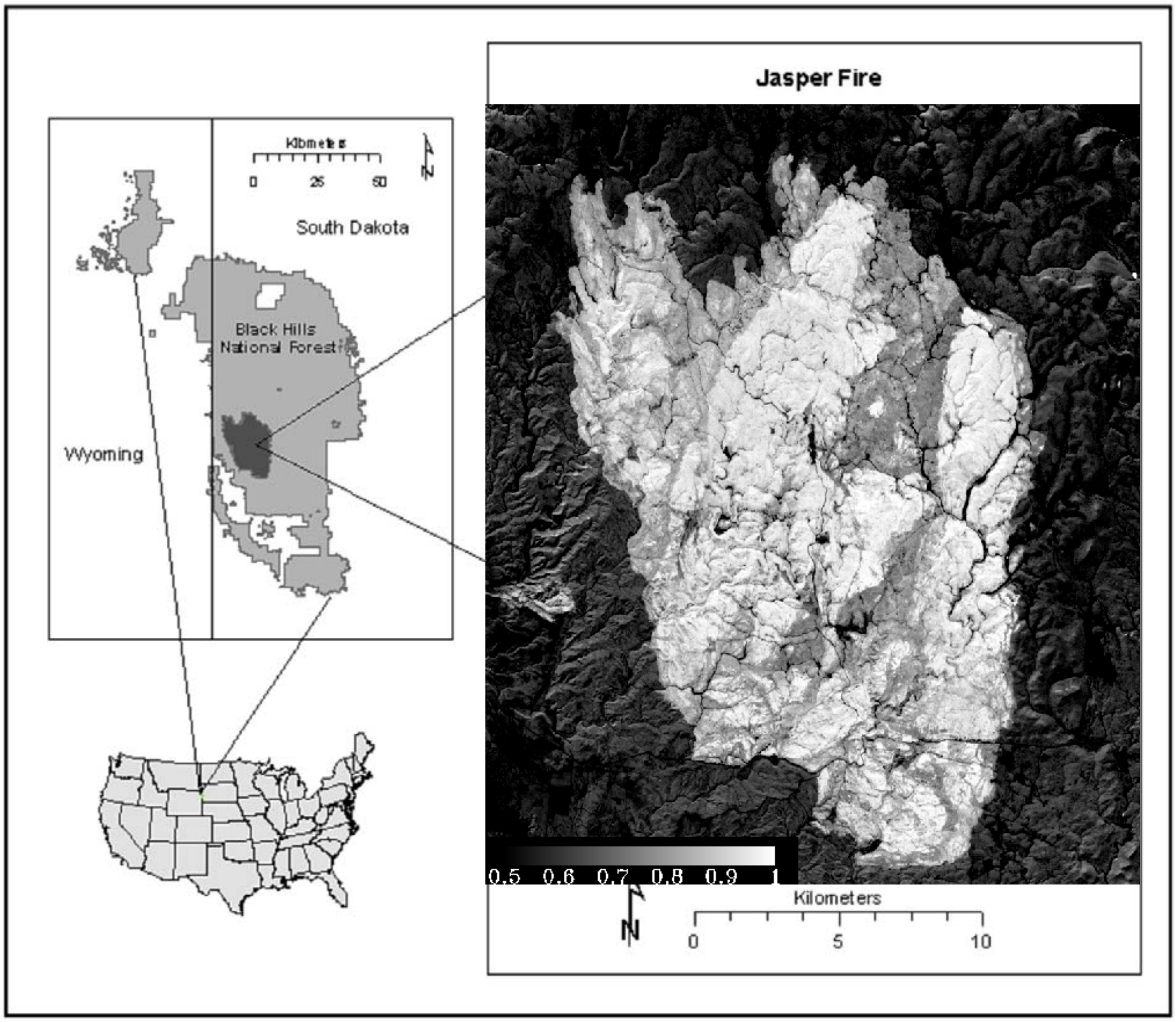

Figure1. The location of the Jasper fire, South Dakota (USA). The image insert is the fraction char cover image produced using the immediate post-fire Landsat image.

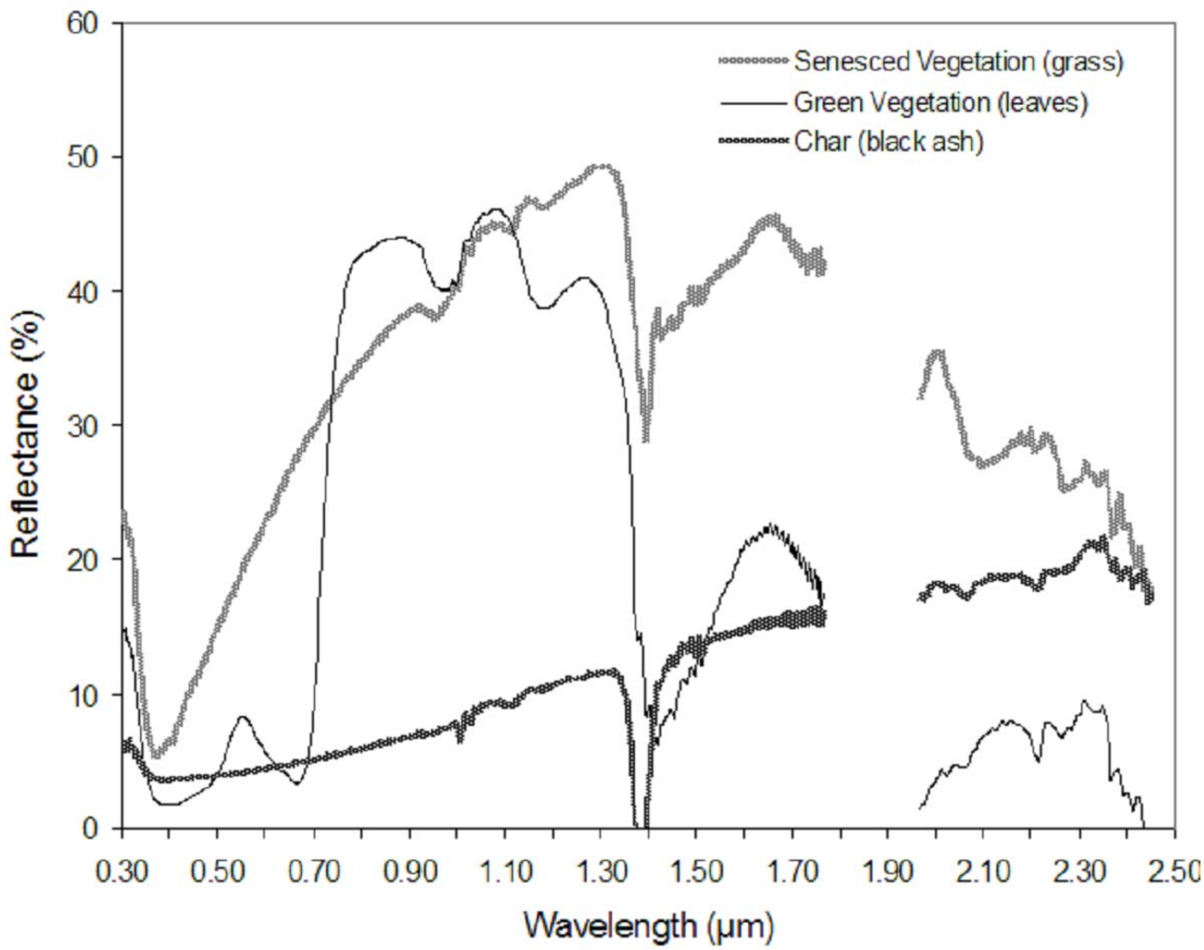

Figure 2. Generic spectral reflectance curves of green vegetation, senesced vegetation, and char (black ash). Spectra were acquired by Smith *et al.* (2005). The data gap about 1.8 µm represents the dominant water absorption feature where data quality is insufficient for analysis.

Figure 3. Left image shows a 1-yr post-fire view of a ponderosa pine forest burned by non-stand replacing fire. Right image highlights a typical scorched bole, as measured in the field. (b/w in print, color on-line)