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Research note

Evaluation of linear spectral unmixing and ΔNBR for predicting post-fire recovery in a North American ponderosa pine forest

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The Differenced Normalized Burn Ratio (ΔNBR) is widely used to map post-fire effects in North America from multispectral satellite imagery, but has not been rigorously validated across the great diversity in vegetation types. The importance of these maps to fire rehabilitation crews highlights the need for continued assessment of alternative remote sensing approaches. To meet this need, this study presents a first preliminary comparison of immediate post-fire char (black ash) fraction, as measured by linear spectral unmixing, and ΔNBR, with two quantitative one-year post-fire field measures indicative of canopy and sub-canopy conditions: % live tree and dry organic litter weight (gm^{-2}). Image analysis was applied to Landsat 7 Enhanced Thematic Mapper (ETM+) imagery acquired both before and immediately following the 2000 Jasper Fire, South Dakota. Post-fire field analysis was conducted one-year post-fire. Although the immediate post-fire char fraction (r^2=0.56, SE=28.03) and ΔNBR (r^2=0.55, SE=29.69) measures produced similarly good predictions of the % live tree, the standard error in the prediction of litter weight with the char fraction method (r^2=0.55, SE=4.78) was considerably lower than with ΔNBR (r^2=0.52, SE=8.01). Although further research is clearly warranted to evaluate more field measures, in more fires, and across more fire regimes, the char fraction may be a viable approach to predict longer-term indicators of ecosystem recovery and may potentially act as a surrogate retrospective measure of the fire intensity.

1. Introduction

Wildfires have short- and long-term effects on ecosystem condition and function (Lentile *et al.* 2006a). Vegetation response and rates of change following fire have commonly been used to gauge ecosystem recovery and have widespread implications for carbon accumulation and hydrological processes (Lewis *et al.* 2005). Prior research to remotely infer post-fire ecosystem condition has mainly applied the Normalized Difference Vegetation Index (NDVI: Rouse *et al.* 1974) and the Differenced Normalized Burn Ratio (ΔNBR: Key and Benson 2006). NDVI has been applied to map the extent of fires (e.g., Smith *et al.* 2002), while NDVI temporal series (months to years) have been used to monitor vegetation recovery

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within California chaparral (Henry and Hope 1998) and Spanish grasslands and forests (Diaz-Delgado *et al.* 2003).

In North American forests, the ΔNBR has been widely applied as a coincident (one year post-fire) measure of canopy effects (van Wagdentonk *et al.* 2004, Brewer *et al.* 2005, Cocke *et al.* 2005). ΔNBR is typically compared to the Composite Burn Index (CBI) field measure (van Wagtendonk *et al.* 2004, Cocke *et al.* 2005, Epting *et al.* 2005), which is an integrative measure, based on qualitative assessment of post-fire effects across understory and overstory strata. A dominant concern is that ΔNBR exhibits a non-linear asymptotic relationship with CBI (van Wagdentonk *et al.* 2004, Cocke *et al.* 2005) that varies with sensor spatial resolution (van Wagtendonk *et al.* 2004) and environment (Epting *et al.* 2005). Further concerns about ΔNBR include its lack of quantitative calibration and its performance as a predictor, rather than a measure of various post-fire ecosystem responses (Smith *et al.* 2005, Lentile *et al.* 2006a, Roy *et al.* 2006).

Linear spectral unmixing has been widely applied to produce maps of the area burned (e.g., Cochrane and Souza 1998, Vafeidis and Drake 2005; Smith *et al.* 2007); however, little research has explored its application for measuring the variation in fire effects within a burned area. Consequently, Lentile *et al.* (2006a) proposed that the proportion of black ash (i.e., char) within a pixel might provide a quantitative measure of post-fire ecological change. Therefore, the objective of this study is to preliminarily evaluate both the immediate post-fire char fraction and ΔNBR for predicting one-year post-fire field measures of canopy and sub-canopy conditions.

2. Methods

2.1 *Study area and field methods*

The study was centred on the Jasper Fire, which during nine days in 2000 burned ~33 800 ha in the South Dakota Black Hills (figure 1). A complete description of the fire regime, study area and field methods are provided in Lentile (2004) and Lentile *et al.* (2005, 2006b). Ponderosa pine (*Pinus ponderosa*) stands dominate the area burned by the Jasper fire, although quaking aspen (*Populus tremuloides* Michx.) stands and small meadows were also present. In 2001, 66 study sites were established in ponderosa pine stands and 14 study sites in aspen stands within the Jasper fire perimeter. Each ponderosa pine site consisted of three 0.03 ha tree plots located at bearings 0°, 135°, and 225° azimuth 20 m from the site centre. Each site in aspen consisted of one 0.03 ha tree plot. Study sites were similar in respect to aspect, slope (5–13%), elevation (1500–2100 m) and soil type (alfisols, mollisols and inceptisols). The percentage of live trees, which is the proportion of trees within a plot that survived the fire, was calculated for each site. Line transects were established at 90° and 270° bearings with the site centre as the midpoint. Forest floor samples (0.025 m^2) were collected at six points offset 2 m to the south of the line transect. Forest floor biomass collections were oven-dried and weighed to provide an estimate of the organic litter weight. Samples were then combusted to correct for soil and ash weight.

2.2 *Remote sensing data and methods*

Landsat ETM+ images of the study area were acquired (18 August, 1999, 14 September 2000) and converted into the top-of-atmosphere reflectance using the

COLOUR FIGURE

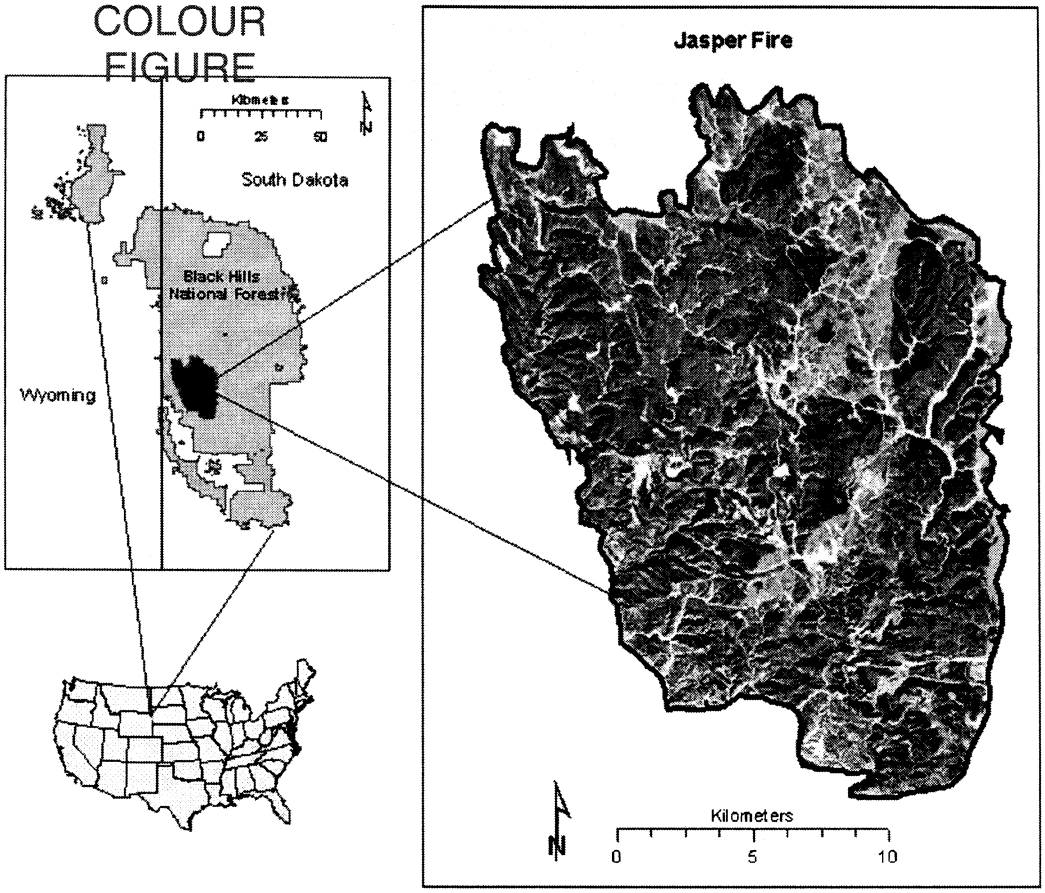

Figure 1. The Jasper fire was located in western South Dakota on the Black Hills National Forest. Jasper fire centre latitude is 43°48′ 56″ N and longitude is 103°52′ 37″ W. The post-fire Landsat 7 image (7-4-3 false-colour composite) was acquired on 14 September 2000. The entire area of the insert represents the area burned by the Jasper fire.

standard Landsat 7 calibration equations (http://landsathandbook.gsfc.nasa.gov/handbook.html). The post-fire Landsat ETM+ imagery was 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). Following Cocke *et al.* (2005), the Differenced Normalized Burn Ratio (ΔNBR), defined by $NBR_{prefire}-NBR_{postfire}$, where $NBR=(TM4-TM7)/(TM4+TM7)$, was calculated (TM# denotes the reflectance of Landsat band #). The ΔNBR image was then scaled by multiplying each value by 1000.

The fraction of char (black ash) within each Landsat pixel was determined using linear spectral unmixing (Settle and Drake 1993). Importantly, the assumption of linear mixing has been shown to be valid when considering fire-affected surface mixtures (Smith *et al.* 2005). Following Smith *et al.* (2007), generic spectrums of senesced vegetation, green vegetation, and char that were collected with a GER 3700 field spectroradiometer (figure 2) were applied in this analysis as the spectral reflectance curves of these generic surfaces are broadly similar across different environments (Elvidge 1990, Smith *et al.* 2005). Linear spectral unmixing was applied using the IDL/ENVI (version 4.2) with the 'sum to 1' constraint applied (Settle and Drake 1993). This constraint ensures that all the fractions within a pixel

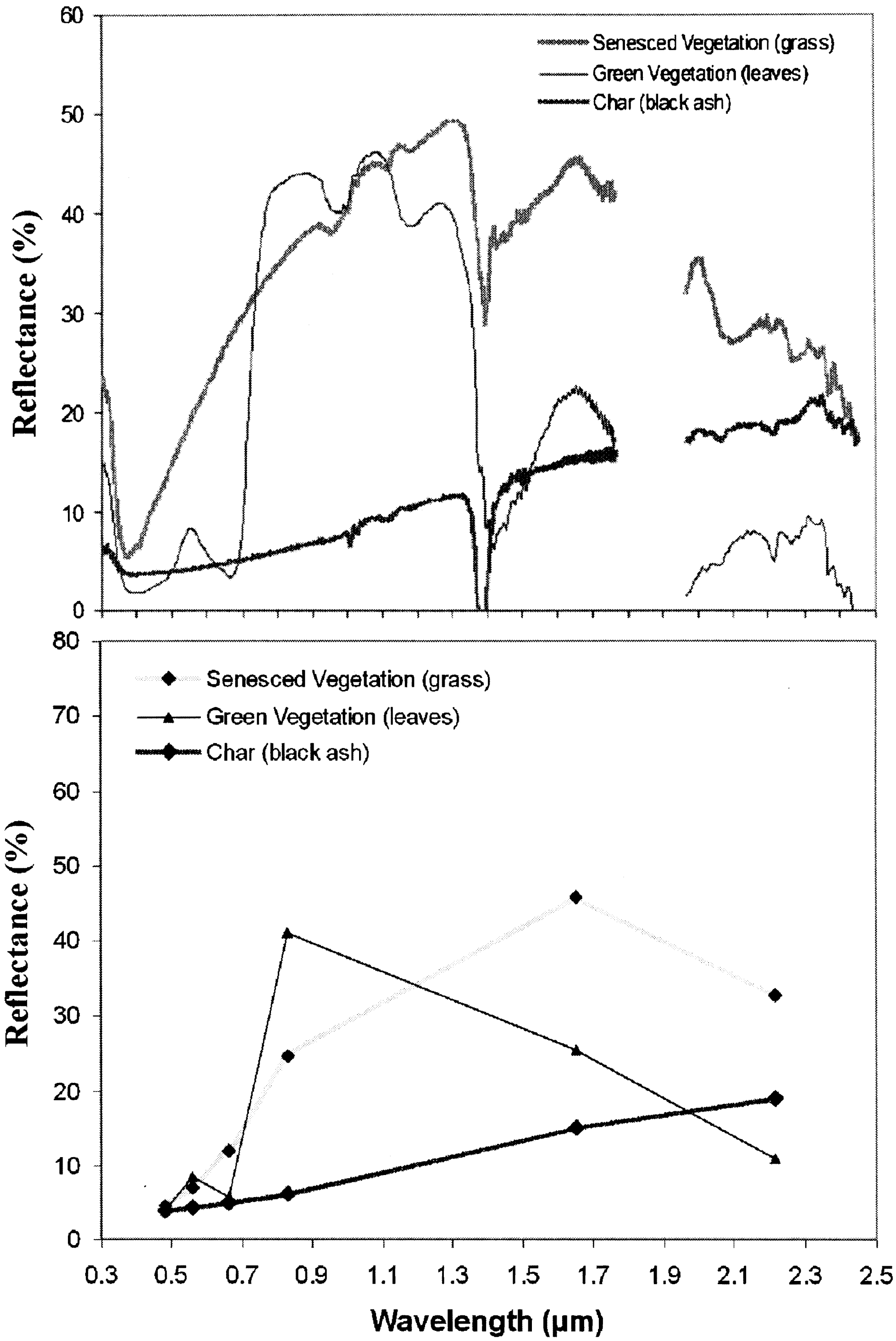

Figure 2. Generic spectral reflectance curves of green vegetation, senesced vegetation, and char (black ash). Spectra were acquired by Smith *et al.* (2005) from a woodland savannah environment. The data gap at ~1.8 μm represents the dominant atmospheric water absorption feature where data quality is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

sum to 1, although it remains possible for individual class fractions to be negative or to exceed 1. The mean ΔNBR and char fraction measures were then extracted for each plot using the ARC software package (ESRI, Redlands, CA, USA).

3. Results and discussion

Both remote measures, i.e., ΔNBR and the char fraction, provided a reasonable and comparable prediction of the one-year post-fire canopy condition metric of percentage live trees (figure 3A, B). The char fraction method did exhibit a marginally higher r^2 and a lower standard error (figure 3A) compared to ΔNBR (figure 3B). Figures 3A and B illustrate that both the char fraction and ΔNBR have values present in sites where no trees survived (0% live tree), suggesting that these measures are not optimal as diagnostic measures of one-year post-fire tree mortality. This could be partly due to the sensing of dead standing trees in heavily forested areas, rather than solely surface components, as measures of canopy light interception at the high "severity" sites indicated that only 80% of the full sunlight

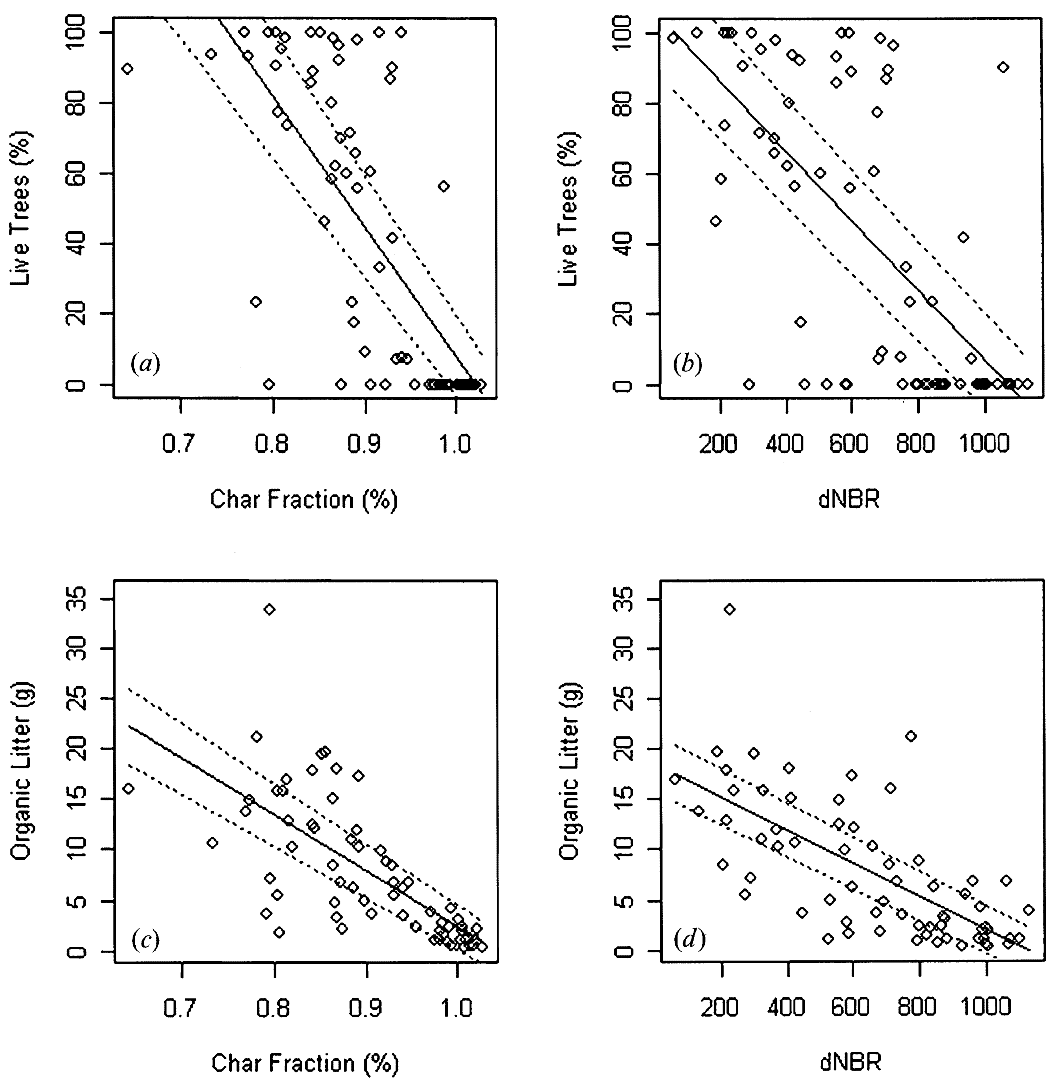

Figure 3. Scatter plots depicting the relationships between each immediate (Year 0) remote post-fire measure and canopy and sub-canopy one-year post-fire indicators of ecosystem conditions. In each case the solid line represents the linear line-of-best-fit.table Regression statistics: (A) $r^2=0.56$, SE=28.03, $y=-370*x+378$; (B) $r^2=0.55$, SE=29.69, $y=-0.10*x+103.9$; (C) $r^2=0.55$, SE=4.78, $y=-58*x+61$; and (D) $r^2=0.52$, SE=8.01, $y=-0.02*x+24.1$. The dashed lines indicate in each case the 95% confidence intervals.

actually reached the forest floor. The high range of ΔNBR values (entire calculated range) is also potentially the result of rapid understory vegetation recovery occurring within severely burned areas that were subject to stand-replacing fires (i.e., areas with none or little one-year % live tree). Although all of the sites that we analysed had moderate to high pre-fire canopy cover (i.e., were forested), high ΔNBR values may be associated with areas of low pre-fire canopy cover, such as savannahs or meadows, commonly found in ponderosa pine forests throughout the western United States. Both ΔNBR and the char fraction provided improved predictions of the one-year post-fire % live tree when compared to the green fraction (r^2=0.49, SE=29), which was also an output of the linear spectral unmixing. This is presumably because the green fraction represents immediate canopy condition, whereas in such fires many trees exhibit mortality due to thermal girdling, resulting in a delayed reduction in canopy cover that may take from months to years to become apparent (Thies *et al.* 2006). Furthermore, in a model developed to predict post-fire tree mortality, Keyser *et al.* (2006) concluded that stem and cambial damage (estimated from the percentage of the bole circumference charred below 30 cm) was a significant predictor of post-fire tree mortality of trees <40 cm diameter breast height (DBH).

Each remote measure provided a comparable coefficient of determination (r^2~0.50) for the prediction of the sub-canopy metric of organic litter weight. However, the standard error of the weight of organic litter for ΔNBR (r^2=0.52, SE=8.01) was considerably higher than that reported for the char fraction (r^2=0.55, SE=4.78). Comparison of figures 3C and D show that when the weight of organic litter dropped to less than 1 g m^{-2} (arbitrarily selected), the minimum char fraction value was 0.98 with the corresponding minimum ΔNBR at 792. This represents 4% and 29% of the dynamic range of each measure respectively. Note, however, each of the char fractions and ΔNBR were similarly variable at organic litter weights exceeding 15 g m^{-2}. Thus, preliminary results demonstrate that the char fraction is potentially an improved measure of the combined degree of litter consumption and subsequent litter recovery. This is important, as litter recovery has been shown to be particularly influential in mitigating post-fire erosion (Robichaud 2004), thus accurate prediction could assist managers with strategic treatment of severely burned areas. The ability of any immediate post-fire remote sensing measure to predict the condition on a sub-canopy metric such as litter organic weight cannot be overstated, as one might expect the canopy to mask such information from view. Based on these results we hypothesize that the char fraction value may be considered as a potential retrospective surrogate measure of the fire intensity, as the fires of higher intensity might be expected to combust more of the pre-fire canopy (resulting in an increased char fraction). We would also expect such higher intensity fires to consume more litter and result in a higher degree of delayed crown removal (due to tree mortality via girdling), which would reduce the one-year post-fire % live tree cover.

4. Conclusions

In this preliminary study, the application of the linear spectral unmixing-derived measure of immediate post-fire char fraction was a marginally improved predictor of one-year post-fire ponderosa pine canopy and sub-canopy conditions, compared to the immediate ΔNBR spectral index. We acknowledge that ΔNBR and the qualitative CBI are primarily management tools used to measure coincident one-year

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post-fire canopy condition. However, the necessity of quantitative approaches to better link remotely sensed data with predictions of fire-related impacts on biogeochemical and hydrological cycles should not be understated. Further research is clearly warranted to expand this analysis with data from several other large North-American wildfires and to investigate other one-year or longer-term field measures to determine the suitability of this approach to remotely predict measures of ecosystem recovery. Research is also warranted to repeat this analysis with spectral end-members collected from North American environments to evaluate the assumption of similarity of the spectra between the collected and applied study environments.

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