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# Synergy of VSWIR (0.4–2.5 μm) and MTIR (3.5–12.5 μm) data for post-fire assessments

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ABSTRACT

Post-fire effects assessments are crucial to evaluate the impact of fire on ecosystems. They are helpful in planning post-fire rehabilitation and useful for reducing uncertainties in current wildfire emission estimates. We have used MODIS/ASTER (MASTER) airborne simulator data over the 2011 Canyon fire in California, USA to evaluate the potential synergy between visible to short-wave infrared (VSWIR, 0.4–2.5 μm) and mid to thermal infrared (MTIR, 3.5–12.5 μm) data in a post-fire environment. We applied Multiple Endmember Spectral Mixture Analysis (MESMA) inputting five endmembers: char, green vegetation, non-photosynthetic vegetation (NPV), substrate and shadow. Results revealed that fractional cover estimates of char, NPV and substrate are 5–7% better when VSWIR–MTIR data were combined, compared to using only VSWIR data. Combined VSWIR–MTIR imagery will become available at pixel sizes smaller than 100 m with future satellite sensors, such as the Hyperspectral Infrared Imager (HyspIRI). The MESMA-derived char fractional cover was also shown to be strongly correlated with the Geo Composite Burn Index (GeoCBI, $R^2_{adj}=0.82$) and the percentage of black trees and shrubs ($R^2_{adj}=0.66$) measured in the field. SMA-derived char fractions provide quantitative abundance maps which should prove valuable for improving wildfire emission estimates by refining burning efficiency values.

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## 1. Introduction

Wildfires can result in heterogeneous burned areas. This heterogeneity originates from both unburned islands and differences in fire severity. Fire severity is defined as the degree of environmental change caused by a fire (Key & Benson, 2005; Veraverbeke et al., 2010a). Remotely sensed fire severity maps are currently operationally used in the USA by the Burned Area Emergency Response (BAER) teams to coordinate post-fire rehabilitation efforts (Parsons et al., 2010). Fire severity data may also be of interest in the estimation of wildfire emissions (De Santis et al., 2010; French et al., 2008a; Kasischke et al., 2011). Current wildfire emission models typically assume a fixed combustion factor, also referred to as burning efficiency, for each major vegetation type (de Groot et al., 2009; van der Werf et al., 2010) which leads to significant uncertainties in emission estimates (Brown et al., 2004; French et al., 2004). Fire severity data have the potential to improve burning efficiency estimates across regions and time (De Santis et al., 2010; Kasischke et al., 2011).

The differenced Normalized Burn Ratio (dNBR) has become the standard method to assess fire severity using remote sensing data, mostly from Landsat imagery (a.o. Epting et al., 2005; French et al., 2008a, 2008b; Key & Benson, 2005; Lopez-Garcia & Caselles, 1991; Veraverbeke et al., 2010a). Although many studies have demonstrated a moderate to high correlation between dNBR values and field measures of severity (a.o. De Santis & Chuvieco, 2007; Epting et al., 2005; van Wagtendonk et al., 2004; Veraverbeke et al., 2010a, 2011a), the dNBR approach has been criticized (a.o. De Santis & Chuvieco, 2007; Epting et al., 2005; Escuin et al., 2008; Murphy et al., 2008; Roy et al., 2006; Smith et al., 2010; van Wagtendonk et al., 2004; Veraverbeke et al., 2010a, 2010b, 2010c, 2011a; Verbyla et al., 2008). A major drawback of the dNBR approach is that without field calibration it lacks biophysical meaning (Hudak et al., 2007; Lentile et al., 2006). While the site-specific empirical relationships between field and remotely sensed fire severity data justify the operational use of the dNBR for post-fire management purposes (Eidenshink et al., 2007; Key & Benson, 2005), dNBR values are of less value use for refining burning efficiency values across regions since the empirical relationships in one region cannot be easily scaled to another region. To achieve this, a remote sensing approach is needed that more directly outputs the fraction of burning or vegetation mortality and does not require tuning to every region (Kasischke et al., 2011; Lentile et al., 2006; Smith et al., 2007).

Spectral Mixture Analysis (SMA) is a well-known remote sensing technique that is used to determine the sub-pixel fraction of cover of different endmembers, which are assumed to represent the spectral variability among the dominant ground cover classes (Adams et

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al., 1986; Roberts et al., 1998). A major advantage of SMA is its ability to detect low cover fractions, something which remains difficult with the spectral index approach (Elmore et al., 2000; Henry & Hope, 1998; Rogan & Franklin, 2001). Moreover, SMA directly results in quantitative abundance maps, without the need of an initial calibration based on field data as with spectral indices (Somers et al., 2010; Veraverbeke et al., 2012a; Vila & Barbosa, 2010). To account for endmember variability, several authors have suggested evaluating multiple endmember combinations from the spectral library instead of using a fixed mean signature per endmember (Asner & Lobell, 2000; Roberts et al., 1998). This method is widely known as MESMA (Roberts et al., 1998). Several authors have applied SMA in the visible to short-wave infrared (VSWIR, 0.4–2.5 μm) spectral domain in post-fire effects studies (Hudak et al., 2007; Kokaly et al., 2007; Lewis et al., 2007; Robichaud et al., 2007; Rogan & Franklin, 2001; Smith et al., 2007). While Rogan and Franklin (2001) and Kokaly et al. (2007) demonstrated the usefulness of SMA-derived fractions in post-fire classification schemes, other studies found significant relationships between SMA-derived fractional cover and field data of fractional cover (Hudak et al., 2007; Lewis et al., 2007, 2011; Robichaud et al., 2007). Smith et al. (2007) found a significant relationship between SMA-derived char fractions and percentage live trees. Several authors have highlighted the potential of SMA-derived char fractions as an indicator for fire severity (Hudak et al., 2007; Lentile et al., 2006; Smith et al., 2005).

In burned area applications, researchers have found that enhancing existing spectral indices with thermal infrared (TIR, 8–12.5 μm) data results in a better separability between burned and unburned areas (Cahoon et al., 1994; Cao et al., 2009; Holden et al., 2005; Lambin et al., 2003; Veraverbeke et al., 2011b). Holden et al. (2005) demonstrated that enhancing the NBR with Landsat's thermal band improved identifying burned areas for two wildland fires in New Mexico, USA. Veraverbeke et al. (2011b) compared 20 different spectral indices and concluded that the NBR enhanced with thermal emissivity data was the best index for separating burned areas. In addition, it is well known that the mid infrared (MIR, 3.5–4 μm) spectral region is associated with a strong post-fire reflectance increase, which has been utilized for burned area mapping purposes (Barbosa et al., 1999; Libonati et al., 2010, 2011; Pereira, 1999; Veraverbeke et al., 2011b). Recently, Veraverbeke et al. (2012b) revealed a SWIR–MIR index (SMI) with strong potential for fire severity mapping. The single date SMI obtained correlations with field data of severity similar to the bi-temporal dNBR (Veraverbeke et al., 2012b). These studies all elaborated on improving traditional VSWIR indices by adding mid to thermal infrared (MTIR, 3.5–12.5 μm) data. In this study we include all available spectral bands by applying MESMA, compared to selected band of spectral indices, to evaluate the full potential of the synergy between VSWIR and MTIR data for post-fire effects studies. More specifically, we aim to (i) explore the potential of the VSWIR–MTIR synergy to derive char fractional cover, and (ii) assess the performance of MESMA-derived char fractional cover as indicator of fire severity.

## 2. Methodology

### 2.1. Study area

From September 4 to 10, 2011 approximately 5900 ha was burned during the Canyon fire in Kern County, CA which was ignited by a plane crash (Fig. 1). The fire burned a mix of grass, shrub, oak and pine trees in steep rugged terrain. The main shrub species were chamise (*Adenostoma fasciculatum*) and Manzanita species (*Arctostaphylos* spp.), whereas California black oak (*Quercus kelloggii*), Jeffrey pine (*Pinus jeffreyi*) and Ponderosa pine (*Pinus ponderosa*) were the main tree species. In the southeastern part of the burn the fire burned out of the hills and onto the desert floor, composed of sparse shrub and grass.

### 2.2. Field data

#### 2.2.1. Spectral library

In October 2011, field samples of the dominant ground cover classes (char, green vegetation, non-photosynthetic vegetation (NPV) and substrate) were collected from multiple locations in the area burned by the Canyon fire. Three char, four vegetation, three NPV and three substrate samples were acquired and transferred to the Jet Propulsion Laboratory (JPL) for in-lab measurements. The substrate samples were unaffected by the fire and represent the soils and rocks in the study area. Measurements in the 0.4–2.5 μm spectral domain were obtained with an Analytic Spectral Devices (ASD) spectrometer under artificial lighting conditions with an ASD Pro lamp. Reflectance was calibrated using a white spectralon panel. Measurements in the 2.5–15 μm spectral range were acquired using a Nicolet 520 Fourier transform infrared (FT-IR) spectrometer with an integrating sphere. A background diffuse gold plate spectrum was used to remove background radiation from the sample spectra (Baldridge et al., 2009). For the vegetation class we also collected top-of-canopy measurements (TOC) of unburned trees and shrubs in the burned area in the 0.4–2.5 μm spectral range with the ASD field spectrometer. Due to the lack of a mounting device, we were restricted to trees and shrubs smaller than 2 m. The majority of the vegetation in the study area was smaller than 2 m and the different vegetation measurements were representative for the variability in vegetation in the study area. These TOC measurements were obtained within 1 h of local solar noon on clear-sky days. We considered TOC data as the most appropriate vegetation measurement in our study, however, acquiring TOC vegetation spectra in the 2.5–15 μm range is a difficult task. Therefore, our in-lab leaf measurements in the 2.5–15 μm range were subjected to an amplitude translation to match the TOC measurements in the 0.4–2.5 μm range. Given the very low reflectance of vegetation beyond 2.5 μm (Kaufman & Rehmer, 1994) this data modification had very little impact on the original reflectance values. Moreover, this processing step was crucial to create consistent TOC data. The shadow spectrum was assumed to be a uniformly dark component and was modeled as a flat 1% reflectance (Lelong et al., 1998; Veraverbeke et al., 2012a, 2012b). Fig. 2 shows the mean spectral signatures of each ground cover class in the 0.4–13 μm region.

#### 2.2.2. Fire severity data

To assess fire severity in the field, 54 Geo Composite Burn Index (GeoCBI) plots were collected in October 2011. The location of the field plots is represented in Fig. 1. The CBI is an operational tool to assess fire severity in the field (Key & Benson, 2005). De Santis and Chuvieco (2009) proposed a modified version of the CBI, called the GeoCBI. The most important difference with the CBI is that the GeoCBI takes into account the fractional cover of the different vegetation strata and as consequence better reflects the spectral mixture of the different component as perceived from remote sensing. The GeoCBI divides the ecosystem into five different strata, one for the substrates and four vegetation layers. These strata are: (i) substrates, (ii) herbs, low shrubs and trees less than 1 m, (iii) tall shrubs and trees of 1 to 5 m, (iv) intermediate trees of 5 to 20 m and (v) big trees higher than 20 m. In the field form (Table 1), 20 different factors can be rated (e.g. soil and rock cover/color change, % LAI change, char height) but only those factors present and reliably rateable, are considered. The rates are given on a continuous scale between zero and three and the resulting factor ratings are averaged per stratum. Based on these stratum averages, the GeoCBI is calculated in proportion to their corresponding fraction of cover, resulting in a weighted average between zero and three that expresses fire severity. The fractional cover of each vegetation layer characterizes the stratum's percentage of vegetation cover relative to the total plot area (De Santis & Chuvieco, 2009).

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