Remote Sensing of Environment 154 (2014) 153–163

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Assessing fire severity using imaging spectroscopy data from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and comparison with multispectral capabilities

Sander Veraverbeke [a,b,*], E. Natasha Stavros [b], Simon J. Hook [b]

[a] Department of Earth System Science, University of California, 2224 Croul Hall, Irvine, 92697 CA, USA
[b] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena 91109, CA, USA

ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form 19 August 2014
Accepted 20 August 2014
Available online 16 September 2014

Keywords:
Fire severity
EnMAP
HyspIRI
PRISMA
Hyperspectral
Wildland fire
Forest fire
AVIRIS
OLI
Weighted multiple endmember spectral mixture analysis (wMESMA)

ABSTRACT

Fire severity, the degree of environmental change caused by a fire, is traditionally assessed by broadband spectral indices, such as the differenced Normalized Burn Ratio (dNBR) from Landsat imagery. Here, we used an alternative indicator, the burned fraction derived from spectral mixture analysis (SMA), to evaluate and compare the performance for assessing fire severity of broadband and narrowband imaging spectroscopy (IS) data in the visible to shortwave infrared (VSWIR, 0.35–2.5 μm). We used the band specifications of the broadband Operational Land Imager (OLI) and the narrowband Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). We integrated two techniques to account for endmember variability in the unmixing process, spectral weighting and iterative unmixing, in a model referred to as weighted multiple endmember SMA (wMESMA). Based on a separability index, we evaluated the separability between the different ground components, or endmembers, that comprise post-fire environments (char, green vegetation (GV), non-photosynthetic vegetation (NPV) and substrate). We found that the near infrared region (0.7–1.3 μm) had the highest discriminatory power, followed by the shortwave infrared 2 (SWIR2, 2–2.4 μm), SWIR1 (1.5–1.7 μm) and visible (0.35–0.7 μm) regions. Individual narrowbands did not substantially outperform individual broadbands, however, the higher data dimensionality of IS resulted in significantly improved post-fire fractional cover and burned fraction estimates compared to multispectral data. Multispectral data captured a fair amount of the variability in fire severity conditions as represented by the different fractional cover estimates of the endmembers in both a multispectral narrow- and broadband scenario, however, fractional cover estimates derived from IS data using all viable bands were significantly better. This demonstrated the benefits of IS over traditional multispectral data to assess fire severity and also showed that the additional information gain was the result of higher data dimensionality and not because of certain narrowbands capturing narrow spectral features. In addition, we found that the burned fraction derived from all viable AVIRIS bands over a fire in California, USA, was highly correlated with two field measures of fire severity (Geo Composite Burn Index: $R^2 = 0.86$, and the percentage black trees and shrubs: $R^2 = 0.65$). Formal quantification of potential improvements of IS over multispectral methods is important with the advent of upcoming spaceborne IS missions (e.g. the Environmental Mapping and Analysis Program and Hyperspectral Infrared Imager). Our analysis showed that IS data when combined with advanced analysis techniques significantly improved fire severity assessments. The improvements of using IS data require higher computational cost and advanced processing, thus multispectral data might still suit the needs of certain applications such as rapid fire damage assessments and global analysis of spatio-temporal fire severity patterns.

1. Introduction

Wildfire is common in many areas of the world, sometimes at great social and economic cost (e.g. loss of infrastructure or human life) or with lasting ecological effects, thus there is a need to understand and quantify its impact. The term fire severity is often used to broadly define the degree of environmental change caused by fire immediately post fire (Key & Benson, 2006; Lentile et al., 2006; Veraverbeke, Lhermitte, Verstraeten, & Goossens, 2010). Specifically, fire severity quantifies short-term effects from fire like fuel consumption and soil alteration (Lentile et al., 2006) and is usually measured in an initial assessment (Key & Benson, 2006). Another term that is often used interchangeably with fire severity is burn severity, which represents both short and long term effects (e.g. post-fire recovery) and is usually measured in an extended assessment (Lentile et al., 2006). While knowledge on burn

* Corresponding author at: Department of Earth System Science, University of California, 2224 Croul Hall, Irvine 92697, CA, USA. Tel.: +1 949 824 9022.
E-mail addresses: Sander.Veraverbeke@uci.edu (S. Veraverbeke), Natasha.Stavros@jpl.nasa.gov (E.N. Stavros), Simon.J.Hook@jpl.nasa.gov (S.J. Hook).

http://dx.doi.org/10.1016/j.rse.2014.08.019

severity can help with long term management plans and understanding the function of fire in a system, fire severity maps can serve as a baseline for field teams to coordinate post-fire rehabilitation efforts (Eidenshink et al., 2007). They can also be ingested in fire emission models (De Santis, Asner, Vaughan, & Knapp, 2010; Veraverbeke & Hook, 2013) to understand air quality patterns and flux estimates of carbon.

Fire severity has often been assessed using field measurements, broadband multispectral remote sensing, or a combination of both. Traditional broadband remote sensing has primarily focused on the differenced Normalized Burn Ratio (dNBR) as an indicator of fire severity (French et al., 2008; Key & Benson, 2006; López-García & Caselles, 1991). The dNBR, which has been primarily calculated from Landsat data, is a spectral index derived as the difference between a normalized ratio of near infrared (NIR) and shortwave infrared (SWIR) reflectance from before and after a fire (Key & Benson, 2006). The removal of vegetation and deposition of charcoal generally results in a reduced post-fire NIR reflectance and elevated post-fire SWIR reflectance (Key & Benson, 2006). Several studies across a variety of ecosystems demonstrated strong correlations between the magnitude of change in post-fire reflectance (dNBR) and field measurements of fire severity (e.g. De Santis et al., 2010; French et al., 2008; Veraverbeke, Verstraeten, Lhermitte, & Goossens, 2010). A drawback of dNBR, however, is that the approach is ecosystem-specific and thus needs initial calibration with field data to derive biophysically meaningful quantitative estimates such as the percentage post-fire tree mortality (Lentile et al., 2006; Veraverbeke & Hook, 2013).

An alternative to dNBR is the use of fractional cover estimates derived from spectral mixture analysis (SMA) to provide quantitative assessments of fire severity. Several studies have found significant relationships between field measurements of severity and SMA-derived fractional char cover (Fernández-Manso, Quintano, & Fernández-Manso, 2009; Jia, Burke, Goetz, Kaufmann, & Kindel, 2006; Jia, Burke, Kaufmann, et al., 2006; Lentile et al., 2009; Lewis et al., 2007, 2011; Quintano, Fernández-Manso, & Roberts, 2013; Robichaud et al., 2007; Smith, Lentile, Hudak, & Morgan, 2007; Sunderman & Wiesberg, 2011; Veraverbeke & Hook, 2013; Veraverbeke, Hook, & Harris, 2012). For example, Veraverbeke and Hook (2013) proposed the burned fraction, a SMA-derivative defined as the ratio between all combusted material (charcoal) and all combustible material (charcoal and vegetation). The burned fraction was highly correlated with fire severity field data and can easily be ingested in emission models. SMA can be performed using broadband spaceborne data like Landsat (Veraverbeke & Hook, 2013), but increased sensitivity may be achieved by using narrowband imaging spectroscopy (IS) data (Jia, Burke, Goetz, et al., 2006; Jia, Burke, Kaufmann, et al., 2006; Kokaly, Rockwell, Haire, & King, 2007; Lewis et al., 2007, 2011; Robichaud et al., 2007; van Wagtendonk, Root, & Key, 2004).

Imaging spectroscopy (IS) is the simultaneous acquisition of spatially coregistered images in many narrow, spectrally contiguous bands, measured in calibrated radiance units, from a remotely operated platform (Schaepman et al., 2009). Since the 1980s, IS had emerged as a powerful analysis method for Earth system research with capabilities beyond what is possible with traditional broadband sensors (Goetz, 2009; Goetz & Curtiss, 1996; Goetz, Vane, Solomon, & Rock, 1985; Green et al., 1998; Schaepman et al., 2009; Vane & Goetz, 1993). IS has been used in a wide variety of earth science investigations focusing on atmospheric gas concentrations (Dennison et al., 2013; Roberts et al., 2010), plant ecology and vegetation status (Asner, Wessman, Bateson, & Privette, 2000; Johnson, Hlavka, & Peterson, 1994; Roberts, Smith, & Adams, 1993; Somers & Asner, 2013; Ustin, Riano, & Hunt, 2012); mineral mapping (Baugh, Kruse, & Atkinson, 1998; Hook, Elvidge, Rast, & Watanabe, 1991; van der Meer & Bakker, 1997), snow and ice properties (Dozier, Green, Nolin, & Painter, 2009; Painter, Dozier, Roberts, Davis, & Green, 2003), coastal and inland waters (Hoogenboom, Dekker, & Althuis, 1998; Salem, Kafatos, Ghazawi, Gomez, & Yang, 2005), urban environments (Roberts, Quattrochi, Hulley, Hook, & Green, 2012; Roessner, Segl, Heiden, & Kaufmann, 2001) and wildfire (Dennison & Matheson, 2011; Dennison & Roberts, 2009; Jia, Burke, Goetz, et al., 2006; Jia, Burke, Kaufmann, et al., 2006; Robichaud et al., 2007; van Wagtendonk et al., 2004). The majority of these studies have been conducted using the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS, Green et al., 1998). Due to limitations associated with airborne data acquisition, these applications are restricted in their geographical scope. Alternative to airborne campaigns and research, some studies have used data from Hyperion, a full-range (0.35–2.5 μm), spaceborne imaging spectroradiometer on the Earth Observing One (EO-1) platform (Middleton et al., 2013). Hyperion serves as heritage orbital spectrometer, but due to its narrow swath wide of 7.7 km, only small local areas have been imaged (Middleton et al., 2013). In the near future, consistent global mapping with imaging spectroradiometers will become possible with the advent of several planned spaceborne IS missions such as the PRecursore IperSpettrale (PRISMA, Labate et al., 2009, www.asi.it/en/activity/earth_observation/prisma_, last accessed on August 18, 2014), the Environmental Mapping and Analysis Program (EnMAP, www.enmap.org, last accessed on August 18, 2014) and the Hyperspectral Infrared Imager (HyspIRI, Chien, Silverman, Davies, & Mandl, 2009, http://hyspiri.jpl.nasa.gov/, last accessed on August 18, 2014).

With upcoming spaceborne missions that will deploy imaging spectroradiometers, a formal comparison between high spectral resolution IS and traditional broadband sensors is required to quantify potential trade-offs between increased data rate and information gain (Goetz, 2009; van Wagtendonk et al., 2004). In this study we used advanced SMA techniques to include endmember variability (Somers, Asner, Tits, & Coppin, 2011) in a post-fire effects unmixing analysis to simulate and compare the performances of an imaging spectroradiometer (AVIRIS) and a broadband sensor (Operational Land Imager (OLI), Irons, Dwyer, & Barsi, 2012). The analysis consisted of two parts. First, using simulated ground component fractions as truth, we compared the performance of narrowband and broadband data for discriminating between the different ground components that make up a post-fire environment (charcoal, vegetation and substrate). We also quantified the improvement in fractional cover estimates generated from SMA using IS compared to broadband data. Second, using fire severity field data as truth, we applied the same methods on AVIRIS data acquired over a fire in California.

2. Methodology

2.1. Study area and AVIRIS

This study uses field and airborne data that were collected over the Canyon Fire in California. The Canyon fire burned approximately 5900 ha in September 2011 (Fig. 1). The fire burned a mix of grass, shrubs, and trees in steep rugged terrain. In the southeast portion within the perimeter, the fire burned out of the hills and onto the desert floor, comprised of sparse shrub and grass. This fire was previously studied using MODIS/ASTER (MASTER) airborne simulator data acquired on November 2, 2011 to assess synergy between visual shortwave infrared (VSWIR) and thermal infrared (TIR) on post-fire effects (Veraverbeke, Hook, & Harris, 2012). Simultaneous with the MASTER data acquisition, AVIRIS data was acquired. The flying height was determined based on the specifications of the MASTER sensor, thus parts of the burn scar were not imaged by AVIRIS (Fig. 1), which has a more narrow swath width.

AVIRIS has 224 contiguous bands with 0.01 μm bandwidths spanning the 0.35–2.5 μm range and provides geolocated, calibrated radiance and with a spatial resolution of 5.5 m. We excluded bands in the main water vapor absorption regions resulting in use of 161 bands. We used the MODTRAN5.2 radiative transfer code (Berk, Anderson,