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Mapping two *Eucalyptus* subgenera using multiple endmember spectral mixture analysis and continuum-removed imaging spectrometry data

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ABSTRACT

Successful discrimination of a variety of natural and urban landscape components has been achieved with remote sensing data using multiple endmember spectral mixture analysis (MESMA). MESMA is a spectral matching algorithm that addresses spectral variability by allowing multiple reference spectra (i.e., endmembers) to represent each material class. However, materials that have a high-degree of spectral similarity between classes, such as similar plant-types or closely related plant species, and large variations in albedo present an ongoing challenge for accurate class discrimination with imaging spectrometry. Continuum removal (CR) analysis may improve class separability by emphasizing individual absorption features across a normalized spectrum. The spectral and structural characteristics common to most *Eucalyptus* trees make them notoriously difficult to discriminate in closed-canopy forests with imaging spectrometry. We evaluated whether CR applied to hyperspectral remote sensing data improved the performance of MESMA in classifying and mapping nine eucalypt tree species according to the two major *Eucalyptus* subgenera, *Eucalyptus* (common name "monocalypt") and *Symphyomyrtus* (common name "symphyomyrtle"). Mixed-canopies comprised of monocalypts and symphyomyrtles are common in Australia, although their spatial distribution is not random. The ability to map these functional types on a landscape-scale could provide important information about ecosystem processes, landscape disturbance history and wildlife habitat. We created a spectral library of 229 pixels from 37 symphyomyrtle tree canopies and 406 pixels from 62 monocalypt tree canopies selected from HyMap imagery and verified with field data. Based on these reference data, we achieved overall classification accuracies at the subgenera-level of 75% (Kappa 0.48) for non-CR spectra and 83% (Kappa 0.63) for the CR spectra. We found that continuum-removal improved the classification performance of most endmember-models, although a larger portion of pixels remained unmodeled with the CR spectra (2%) compared to the non-CR spectra (0%). We utilized a new method for model optimization and created maps of monocalypt and symphyomyrtle distribution in our study area based on our best performing endmember-models. Our vegetation maps were largely consistent with our expectations of subgenera distribution based on our knowledge of the region.

1. Introduction

Our ability to understand, monitor and conserve native landscapes is limited by our lack of knowledge about the composition, structure and disturbance history of ecological communities. Recent advances in airborne and spaceborne hyperspectral remote sensing combined with improved algorithms for spectral discrimination are allowing researchers to map vegetation communities with increasing accuracy (for reviews see, Majeke et al., 2008; Turner et al., 2003; Xie et al., 2008). However, vegetation types that have a high degree of spectral and structural similarity or high intra-species variability present an ongoing challenge for accurate classification and mapping (Clark et al., 2005; Cochrane, 2000; Goodwin et al., 2005; Hestir et al., 2008). Variations in landscape topography, canopy structure and viewing geometry also can reduce the accuracies of classification techniques and spectral matching algorithms that are influenced by albedo (Asner et al., 2000; Dennison et al., 2004; Wu, 2004).

In this study, we investigated whether multiple endmember spectral mixture analysis (MESMA, Roberts et al., 1998) could be used to discriminate *Eucalyptus* trees from the two major subgenera, *Eucalyptus*

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(common name "monocalypt") and *Symphyomyrtus* (common name "symphyomyrtle"), using hyperspectral remote sensing data collected over a forest in southeastern Australia. These two subgenera encompass the majority of eucalypt tree species and represent an important functional type based on general divisions among the physiology (e.g. concentrations of foliar biochemicals) and ecology (e.g. response to fire and salinity) of trees from these two groups (Noble, 1989). Despite these differences, most species within these two subgenera still possess the unfavorable structural characteristics and spectral variability that can frustrate attempts at discrimination on a canopy scale using imaging spectroscopy (Turner et al., 1998). The MESMA approach incorporates spectral variability within material classes, and therefore may be useful for this application.

We further investigated whether a spectral normalization technique, continuum removal (CR), could improve the performance of MESMA, given the variability in reflectance arising from the open-canopy architecture common to eucalypt trees.

We hypothesized that CR-spectra were likely to improve class discrimination by reducing brightness differences and accentuating subtle absorption features. We also tested the hypothesis that those species that were less confidently modeled had particular physiognomic characteristics common to both subgenera. Using our most successful models, we generated maps of the distribution of monocalypt and symphyomyrtle trees in our study area. This research is part of a larger study investigating the use of hyperspectral remote sensing to map habitat for arboreal marsupial folivores.

2. Background

2.1. Spectral mixture analysis

Spectral mixture analysis (SMA) is an analysis technique that models a mixed spectrum as the combination of two or more "pure" spectra, called endmembers (Adams et al., 1986; Gillespie, 1992; Roberts et al., 1993; Settle & Drake, 1993). Endmembers can be derived from the laboratory, field (Roberts et al., 1993), imagery (Dennison & Roberts, 2003a) or even radiative transfer (Painter et al., 1998; Sonnentag et al., 2007). Although multiple near-infrared (NIR) scattering results in non-linear mixing (e.g., Borel & Gerstl, 1994; Roberts et al., 1993; Somers et al., 2009a,b), most often a linear model is assumed. Typical endmembers include one to three bright spectra paired with a dark "shade" or photometric shade endmember to control for brightness. Using a linear mixing model, a mixed spectrum is modeled as the sum of the reflectance of each material within a pixel multiplied by its spectral fraction (Eq. 1):

$$\rho'_\lambda = \sum_{i=1}^{N} f_i * \rho_{i\lambda} + \varepsilon_\lambda \tag{1}$$

where ρ'_λ is the reflectance of a modeled spectrum, $\rho_{i\lambda}$ is the reflectance for endmember i, f_i is the fraction contributed by the endmember, N is the number of endmembers, and ε_λ is the residual term—for a specific wavelength λ. Fractional abundance can be estimated using a variety of approaches, including least squares (Shimabukuro & Smith, 1991), modified Gramm–Schmidt orthogonal decomposition (Adams et al., 1993) or singular value decomposition (Boardman et al., 1995) as three common approaches. Model fit is often assessed using a root mean square error (RMSE) error metric:

$$\text{RMSE} = \sqrt{\frac{\sum_{\lambda=1}^{M} (\varepsilon_\lambda)^2}{M}} \tag{2}$$

where M is the number of bands (Dennison et al., 2004).

Most often, SMA is implemented using a fixed-set of endmembers applied to an entire scene. While this approach has proven to be effective for mapping fractional cover, it fails to account for within-class spectral variability or spatial variability in the spectral dimensionality of the data (Roberts et al., 1998; Sabol et al., 1992; Song, 2005). In an attempt to overcome this limitation, various techniques to address endmember variability and similarity have been developed (e.g., Asner & Lobell, 2000; Bateson et al., 2000; Roberts et al., 1998; Somers et al., 2009a,b). For example, Bateson et al. (2000) incorporated endmember variability into SMA by representing each endmember as a bundle of spectra constructed from the data. Somers et al. (2009a,b) presented an alternative to SMA, Integrated Spectral Unmixing (InSU), that combined reflectance and derivative reflectance features using an automated waveband selection protocol. This method reduced the variability within endmember classes by focusing on a subset of wavelengths. Similarly, Asner and Lobell (2000) used a spectral unmixing algorithm in combination with waveband selection and a normalization technique to reduce endmember variability.

MESMA is an extension of SMA that addresses spectral and spatial variability within material classes by allowing the number and type of endmembers to vary on a per pixel basis (Roberts et al., 1998). Rather than using waveband selection or spectral transformation techniques to reduce endmember variability, MESMA enables the user to select multiple endmembers to represent each material class. Spectral matching can be accomplished with the two-endmember case of MESMA, which is comprised of one class endmember coupled with a shade endmember (Dennison et al., 2007; Roberts et al., 1998). The MESMA approach has been widely used for mapping minerals (Bedini et al., 2009; Li & Mustard, 2003), snow cover and grain size (Painter et al., 1998), fire properties (Dennison et al., 2006; Eckmann et al., 2008), continental-scale land-cover type (Ballantine et al., 2005), urban environments (Powell et al., 2007; Rashed, 2008) and vegetation type and biophysical properties (Dennison & Roberts, 2003a; Roberts et al., 1998; Sonnentag et al., 2007). Recently, techniques to improve MESMA endmember selection (Dennison et al., 2004; Dennison & Roberts, 2003b; Dennison et al., 2007) and an open-source software application (Roberts et al., 2007) have been developed to facilitate its use. However, a limitation of MESMA over spectral matching algorithms that use a similarity metric derived from spectral angles rather than overall reflectance (i.e. Spectral Angle Mapper, SAM, Kruse et al., 1993), is that classification accuracy can be strongly influenced by variations in albedo (Dennison et al., 2004).

2.2. Continuum removal

Continuum removal (CR) is a spectral processing technique that normalizes brightness while emphasizing absorption features (Clark & Roush, 1984). A convex hull, or continuum, is fitted over a spectrum to connect the points of maximum reflectance with a straight line (Fig. 1). The continuum can be applied to selected segments or across the entire spectrum. The peak reflectance points where the actual spectrum meets the continuum line are standardized to a value of one and this value decreases towards zero as the distance between the original spectrum and continuum line increases. The continuum is removed by dividing reflectance value (ρ) of a specific wavelength (λ) by the reflectance value of the continuum ($\rho_{c\lambda}$) at the corresponding wavelength (Eq. 3):

$$\text{CR} = \frac{\rho_\lambda}{\rho_{c\lambda}}. \tag{3}$$

In remotely sensed data, the effects of field of view and photon scattering can alter radiance reaching the sensor (Richards & Jia, 2006). Subtle absorption features in reflectance data are enhanced in the normalization process of CR and their depth and position are not influenced by variations in albedo (Schmidt & Skidmore, 2003).

CR is most often used in spectral data analysis to identify the geological composition of materials and to quantify vegetation biochemistry (Huang et al., 2004; Kruse & Lefkoff, 1993; Mutanga &