ISPRS Journal of Photogrammetry and Remote Sensing 108 (2015) 80–93

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Mapping invasive species and spectral mixture relationships with neotropical woody formations in southeastern Brazil

Cibele H. Amaral [a,*], Dar A. Roberts [b], Teodoro I.R. Almeida [a], Carlos R. Souza Filho [c]

[a] Institute of Geosciences, University of São Paulo, Rua do Lago 562, São Paulo, SP 05508-080, Brazil
[b] Department of Geography, University of California Santa Barbara, 1832 Ellison Hall, Santa Barbara, CA 93106, United States
[c] Institute of Geosciences, University of Campinas, PO Box 6152, Campinas, SP 13083-870, Brazil

ARTICLE INFO

Article history:
Received 11 December 2014
Received in revised form 1 March 2015
Accepted 9 June 2015

Keywords:
Invasive species
Brazilian savanna biome
Hyperspectral data
Multiple endmember spectral mixture analysis

ABSTRACT

Biological invasion substantially contributes to the increasing extinction rates of native vegetative species. The remote detection and mapping of invasive species is critical for environmental monitoring. This study aims to assess the performance of a Multiple Endmember Spectral Mixture Analysis (MESMA) applied to imaging spectroscopy data for mapping *Dendrocalamus* sp. (bamboo) and *Pinus elliottii* L. (slash pine), which are invasive plant species, in a Brazilian neotropical landscape within the tropical Brazilian savanna biome. The work also investigates the spectral mixture between these exotic species and the native woody formations, including woodland savanna, submontane and alluvial seasonal semideciduous forests (SSF). Visible to Shortwave Infrared (VSWIR) imaging spectroscopy data at one-meter spatial resolution were atmospherically corrected and subset into the different spectral ranges (VIS–NIR1: 530–919 nm; and NIR2–SWIR: 1141–2352 nm). The data were further normalized via continuum removal (CR). Multiple endmember selection methods, including Interactive Endmember Selection (IES), Endmember average root mean square error (EAR), Minimum average spectral angle (MASA) and Count-based (CoB) (collectively called EMC), were employed to create endmember libraries for the targeted vegetation classes. The performance of the MESMA was assessed at the pixel and crown scales. Statistically significant differences ($\alpha = 0.05$) were observed between overall accuracies that were obtained at various spectral ranges. The infrared region (IR) was critical for detecting the vegetation classes using spectral data. The invasive species endmembers exhibited spectral patterns in the IR that were not observed in the native formations. Bamboo was characterized as having a high green vegetation (GV) fraction, lower non-photosynthetic vegetation (NPV) and a low shade fraction, while pine exhibited higher NPV and shade fractions. The invasive species showed a statistically significant larger number of spectra erroneously assigned to the woodland savanna class versus the alluvial and submontane SSF classes. Consequently, the invasive species tended to be overestimated, especially in the woodland savanna. Bamboo was best classified using the VSWIR(CR) data with the EMC endmember selection method (User's accuracy and Producer's accuracy = 98.11% and 72.22%, respectively). Pine was best classified using NIR2–SWIR(CR) data with the IES selected endmembers (97.06% and 62.26%, respectively). The results obtained during the two-endmember modeling were fully translated into the three-endmember unmixed images. The sub-pixel invasive species abundance analysis showed that MESMA performs well when unmixing at the pixel scale and for mapping invasive species fractions in a complex neotropical environment, at pixel and crown scales with 1-m spatial resolution data.

1. Introduction

Biological invasion has increased the extinction rates of native species (Vitousek et al., 1996). Some invasive species can modify ecosystems, introducing intolerable or unfavorable conditions for the survival and colonization of native species by changing the frequency and intensity of wildfires, ecosystem hydrology,

* Corresponding author at: Brazilian National Institute for Space Research, Avenida dos Astronautas, 1758, São José dos Campos, SP 12227-010, Brazil. Tel.: +55 12 32086425; fax: +55 12 32086488.

E-mail addresses: cibeleha@gmail.com (C.H. Amaral), dar@geog.ucsb.edu (D.A. Roberts), talmeida@usp.br (T.I.R. Almeida), beto@ige.unicamp.br (C.R. Souza Filho).

http://dx.doi.org/10.1016/j.isprsjprs.2015.06.009
0924-2716/

biogeochemical cycling and erosion rates (Beck et al., 2008). These species exhibit rapid dispersion and nonlinear dynamics; therefore, their synergy with other anthropogenic changes is a major challenge during global change (Burkett et al., 2005; Parry et al., 2007). Due to their importance, the extent and impact of colonization by invasive species must be included in scenarios of global change (Mooney and Hobbs, 2000).

Imaging spectroscopy is one of the most promising technologies for early detection of invasive species and has been used to map perennial pepper weed and water hyacinth in wetlands using logistic regression (Hestir et al., 2008) and leafy spurge in semi-arid shrublands using mixture-tuned matched filters (Williams and Hunt, 2002; Glenn et al., 2005) as some examples. Commonly invasive species represent different optical types in the landscape (Ustin and Gamon, 2010) and therefore can often be discriminated from non-invasive species. One promising technique for mapping invasive species and estimating their fractional abundance is Spectral Mixture Analysis (SMA; Adams et al., 1993), which has been used to map submerged and floating invasive species, as Brazilian waterweed and water hyacinth, in the California Delta ecosystem (Underwood et al., 2006; Hestir et al., 2008).

Multiple Endmember Spectral Mixture Analysis (MESMA; Roberts et al., 1998) is an extension of SMA, in which the number and types of endmembers are allowed to vary on a per pixel basis. MESMA has been used extensively to map invasive species using imaging spectrometry data. For example, Li et al. (2005) and Rosso et al. (2005) used MESMA applied to Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data to identify marshland that included invasive species, such as *Spartina* spp., in the San Francisco Bay, California (USA). Tits et al. (2012) identified *Morella faya* in Hawaii (USA) on AVIRIS and Hyperion images, also using MESMA. Recent research indicates that pre-processing techniques can improve MESMA results. Somers and Asner (2013, 2014) detected invasive species in Hawaii (USA) using unitemporal and multi-temporal Hyperion data and MESMA classification. The authors employed a separability index (SI) and found that selecting spectral features beforehand, while excluding adjacent bands with high correlations, increased the classification accuracy of MESMA. Youngentob et al. (2011) mapped two native subgenera of Eucalyptus in the Tumult region in New South Wales (AUS). The authors applied continuum removal to the spectra; this process normalizes the data and enhances the absorption features (Clark and Roush, 1984). Two Eucalyptus subgenera were detected more effectively by MESMA when using continuum-removed (CR) spectra compared to standard spectra.

Although largely explored in the northern hemisphere, the use of imaging spectroscopy to map invasive species in neotropical biomes in continental South America appears to be lacking. In addition, an understanding of how different pre-processing approaches can improve invasive species mapping using MESMA in these highly biodiverse landscapes is also lacking. Among these landscapes, the Brazilian savanna biome is a hotspot for global biodiversity, even though only 2% of its area is legally protected; it has the richest savanna flora in the world (>7000 species) and a high level of endemism (Klink and Machado, 2005). Virtually all conservation units, such as biological reserves and parks, are currently being invaded by exotic species to varying degrees (Pivello, 2011). In addition to the areas with anthropic disturbances, the open physiognomies of the biome, which allow direct sunlight to reach the lower strata, are under significant colonization pressure due to these invasive species (Pivello et al., 1999).

This study aims to evaluate the performance of MESMA on ProSpecTIR-VS hyperspectral data (357 channels from 400–2500 nm) for the spectral detection and mapping of two invasive species, *Dendrocalamus* sp. (bamboo) and *Pinus elliottii* L. (slash pine), in the Mogi-Guaçu Ecological Park, São Paulo, Brazil. This area contains a wide variety of tree and shrub species, which produces considerable spectral variation in the airborne hyperspectral images acquired for the study. Within this objective, we test whether these invasive species can be spectrally detected in a landscape containing varied woody formations in the tropical Brazilian savanna biome to determine which formation shows the largest estimation errors for the targeted invasive species. We also evaluate possible accuracy improvements through independent visible-near infrared and infrared-shortwave infrared hyperspectral data subsets, both with and without continuum removal in MESMA classifications, while considering different endmember selection methods.

2. Theory section

2.1. Continuum removal

The continuum is a convex hull consisting of straight line segments that connect the ends of the spectrum and/or reflectance peaks in that interval; it is modeled as a mathematical function and can be removed from segments or the entire spectrum to normalize the differences in brightness while highlighting the absorption features present in the interval (Clark and Roush, 1984). During continuum removal, the intersection points are normalized to 1.0 and the reflectance values of the absorption features begin to vary between 1.0 and zero. The continuum is removed (CR) by dividing the reflectance value (ρ) at a given wavelength (λ) by the reflectance value of the continuum ($\rho_C\lambda$) at the same wavelength:

$$CR = \frac{\rho\lambda}{\rho_C\lambda} \quad (1)$$

In vegetation spectroscopy, continuum removal has been used primarily for analyzing absorption features located in the near-infrared (NIR) and shortwave infrared (SWIR) regions, particularly when estimating the non-pigmented biochemical constituents of vegetation, such as nitrogen, lignin and cellulose (e.g., Kokaly and Clark, 1999; Curran et al., 2001; Kokaly, 2001; Huang et al., 2004; Kokaly et al., 2009). This technique has also been applied to preprocess the hyperspectral data for the maps of invasive species in California (USA), as reported by Underwood et al. (2003) and Hestir et al. (2008). In these studies, the authors used this technique to enhance the spectral absorption features of intra-leaf water in the NIR region. Youngentob et al. (2011) also used the continuum-removed spectra to map the two subgenera of eucalyptus in New South Wales (AUS) using MESMA.

2.2. Endmember selection methods

Endmember selection involves identifying the types and numbers of endmembers and their spectral signatures from a spectral library (Somers et al., 2011). Several techniques that capture the smallest number of endmembers representing and modeling the spectral variability of a particular class have been developed for applications in MESMA (Roth et al., 2012).

Roberts et al. (2003) proposed a count-based (CoB) endmember selection in which the optimal endmember is the endmember that models the largest number of spectra within its class. The CoB index (CoBI) was subsequently proposed by Clark (2005) to rank the endmembers according to the ratio obtained between modeled spectra within its class (CoBIn) and modeled spectra outside its class (CoBOut). Dennison and Roberts (2003a) developed endmember average root mean square error (EAR), which uses each spectrum within a class to model all other spectra of that class through a linear SMA. EAR is equivalent to the average root mean