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Retrieval of subpixel *Tamarix* canopy cover from Landsat data along the Forgotten River using linear and nonlinear spectral mixture models

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ABSTRACT

Repeatable approaches for mapping saltcedar (*Tamarix* spp.) at regional scales, with the ability to detect low density stands, is crucial for the species' effective control and management, as well as for an improved understanding of its current and potential future dynamics. This study had the objective of testing subpixel classification techniques based on linear and nonlinear spectral mixture models in order to identify the best possible classification technique for repeatable mapping of saltcedar canopy cover along the Forgotten River reach of the Rio Grande. The suite of methods tested were meant to represent various levels of constraints imposed in the solution as well as varying levels of classification details (species level and landscape level), sources for endmembers (space-borne multispectral image, airborne hyperspectral image and *in situ* spectra measurements) and mixture modes (linear and nonlinear). A multiple scattering approximation (MSA) model was proposed as a means to represent canopy (image) reflectance spectra as a nonlinear combination of subcanopy (field) reflectance spectra. The accuracy of subpixel canopy cover was assessed through a 1-m spatial-resolution hyperspectral image and field measurements. Results indicated that: 1) When saltcedar was represented by one single image spectrum (endmember), the unconstrained linear spectral unmixing with post-classification normalization produced comparable accuracy (OA = 72%) to those delivered by partially and fully constrained linear spectral unmixing (63–72%) and even by nonlinear spectral unmixing (73%). 2) The accuracy of the fully constrained linear spectral unmixing method increased (from 67% to 77%) when the classes were represented with several image spectra. 3) Saltcedar canopy reflectance showed the strongest nonlinear relationship with respect to subcanopy reflectance, as indicated through a range of estimated canopy recollision probabilities. 4) Despite the considerations of these effects on canopy reflectance, the inversion of the nonlinear spectral mixing model with subcanopy reflectance (field) measurements yielded slightly lower accuracy (73%) than the linear counterpart (77%). Implications of these results for region-wide monitoring of saltcedar invasion are also discussed.

1. Introduction

Invasive species threats, which have been recognized as an important component of global environmental change (Drake et al., 1989; Vitousek et al., 1996), demand effective analysis with regional-scale remote sensing measurements. The invasion of saltcedar (*Tamarix* spp.) in the southwestern United States and northern Mexico represents a high priority case, in which remote sensing data plays a crucial role in both management operations and understanding the invasion process (Hunt et al., 2003; Lass et al., 2005). However, the analysis of moderate spatial resolution imagery (10–100 m) that is required for addressing the invasion problem still encounters a number of challenges. For example, recent studies of spectral invariants in canopy radiative transfer functions proposed a simple parameterization of the light–canopy interaction that would allow more accurate estimations of the canopy cover (Huang et al., 2007; Lewis & Disney, 2007; Smolander & Stenberg, 2005). These nonlinear mixture models are, however, difficult to invert, and their application with moderate-resolution imagery is still to be assessed. These issues motivated the present study.

Previous studies have shown that saltcedar habitats can be mapped using remotely sensed data and techniques (1996; Carruthers et al., 2006; Everitt & DeLoach, 1990, Everitt et al., 1992; Hamada et al., 2007). Approaches coupling high spatial resolution and hyperspectral images with conventional pixel-level classifications can achieve high accuracies (Carruthers et al., 2006; Hamada et al., 2007). Such images, however, tend to cover only small areas on the ground and are expensive to acquire, thus limiting their utility for macro-scale monitoring. The application of moderate resolution satellite images, which cover larger areas on the ground, are advantageous in this respect. In recent studies, NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) was successfully used for mapping

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saltcedar habitat suitability at the regional scale (Morisette et al., 2006). The relatively low spatial resolution of MODIS data, however, makes it impossible to detect accurately low-density saltcedar stands (e.g., early invasion stage). In another study along the Arkansas River in Colorado, the near-infrared bands of Landsat TM data have been found effective for discriminating large patches of saltcedar during the leaf-off season (Groeneveld & Watson, 2008). One obvious limitation for moderate-resolution sensors, however, is the difficulty in accurately detecting small extents of saltcedar invasion, which is crucial for effective management (Shafroth et al., 2005). Yet, because the width of saltcedar bands along the river typically varies from a few meters to hundreds of meters, Landsat measurements represent a good compromise between spatial resolution and spatial extent for mapping the distribution of saltcedar. This study hypothesized that the use of subpixel classification methods would further enhance the utility of Landsat data for tackling the saltcedar invasion problem.

Subpixel classification techniques are superior to traditional pixel-level classifications techniques because they allow for the quantification of subpixel species coverage. Three major approaches for subpixel classification have been identified (Eastman & Laney, 2002): 1) spectral mixture analysis (SMA), 2) regressive approaches, such as neural networks, and 3) soft classification methods based on fuzzy sets and probability theories. This study focused on the first approach. The rationale of SMA is that mixed pixels result from a systematic combination of component spectra (endmembers) present in the sensor's instantaneous field of view (IFOV) (Adams et al., 1993; Gillespie, 1992; Milton, 1999. The relative contribution of component spectra is then determined by the inversion of mixture models (Chang & Heinz, 2000; Heinz & Chang, 2001; Hu et al., 1999; Keshava & Mustard, 2002).

The mathematical form of the mixture model is strongly influenced by the definition of the endmembers. While the horizontal mixing of vegetation types across the landscape due to an increase in the IFOV with respect to plant canopy is primarily a linear process (Adams et al., 1995; Roberts et al., 1993), the interaction of light with vegetation components (i.e., leaves, stems, etc.) in the three-dimensional space is highly nonlinear (Borel & Gerstl, 1994; Ray & Murray, 1996; Smolander & Stenberg, 2005). The assumption of a linear mixture process is convenient because the endmembers are, by definition, confined to the extremes of the mixing space (Boardman et al., 1993; Small, 2004). For vegetation mapping, however, the endmembers thus defined may be meaningless or hard to match with ground measurements due to nonlinear mixing processes. Recent studies on canopy radiative transfer functions have led to the development of the canopy spectral invariant theory (Huang et al., 2007; Knyazikhin et al., 1998; Lewis & Disney, 2007), according to which variations of canopy scattering (reflectance plus transmittance) and absorptance are mainly influenced by optical properties (spectral leaf transmittance and reflectance) of individual leaves and two wavelength independent canopy structural variables: the canopy interceptance and the recollision probability. Based on this theory, explicit mathematical relationships of the light–canopy interaction have been developed for single homogeneous canopies with non-reflective background (Smolander & Stenberg, 2005). Interestingly, the algebraic structure of these models holds across multiple mixing scales, from needle/leaf to shoot/branch and from shoot/branch to canopy (2005; Lewis & Disney, 2007, Smolander & Stenberg, 2003). This study hypothesized that proper inversion of this kind of model should lead to improved estimations of subpixel canopy cover of saltcedar.

The general objective of this study was to test linear and nonlinear spectral mixture models in order to identify the best possible classification strategy for repeatable mapping of saltcedar on a regional setting. The specific objectives were:

(1) Assess the role of multiple scattering on canopy reflectance using a modeling approach,
(2) Test whether the level of constraint imposed in the least square inversion of the linear mixture model plays a major role in the accuracy of estimated subpixel canopy coverage,
(3) Determine whether the thematic level at which endmembers are defined has a significant impact on subpixel canopy cover estimations,
(4) Test whether the consideration of the multiple scattering phenomena can lead to increased accuracy in estimating subpixel saltcedar canopy coverage from Landsat data.

In order to attain the above objectives, seven subpixel classification methods were tested. Five of these methods were based on the linear mixture model with varying levels of constraint (unconstrained, sum-constrained, nonnegativity-constrained, fully constrained, and tessellated linear spectral unmixing, Section 3.1). The other two methods were based on a nonlinear mixture model (the fully constrained and the tessellated multiple scattering approximation spectral unmixing methods, Section 3.2). The suite of methods tested involved three spectral libraries that represented three levels of detail: level 1 of a classification system (L1ETM, Section 3.1.2), level 2 with canopy measurements (L2AISA, Section 3.1.2), and level 2 with subcanopy measurements (L2SYNTH, Section 3.2.4).

2. Data used

The study incorporated three data sources for derivation of reference fractions and endmember reflectance spectra (Fig. 1): 1) a Landsat ETM+ image (Section 2.2), 2) an airborne hyperspectral image (Section 2.2), and 3) *in situ* measurements (Section 2.3). The rest of this section provides details on the processing and role of these data sets.

2.1. Study site

A study site was selected on the Forgotten River reach of the Rio Grande River near the town of Candelaria, Texas (Fig. 2). At this site, the riverbanks have been taken over by saltcedar, and the native cottonwood (*Populus* spp) that once dominated the area is completely absent (Everitt, 1998). The vegetation on both banks of the river is composed mostly of saltcedar (*Tamarix chinensis* L.) with some mixes of willow (*Salix* spp). The spatial distribution of saltcedar along the river is variable, due in part to differences in the local hydrologic system. As one moves into the uplands, honey mesquite (*Prosopis* spp) stands are found, although they are generally mixed with other weeds and saltcedar. A giant saltcedar species (*Tamarix aphylla* L. Karst or Athel tamarisk) is also found in the study site, although in very sparse occurrences along the uplands.

2.2. Image acquisition and processing

The Airborne Imaging Spectroradiometer for Applications (AISA) sensor system (Spectral Imaging LTD) was flown over the study site on 21 December 2005. The acquisition time coincided with the time window when saltcedar's foliage turns a yellow-orange to orange-brown color before leaf drop and thus can be more easily discriminated from native mesquite and willow species (Everitt & DeLoach, 1990). The AISA imagery acquired had 61 bands in the spectral range 400–1000 nm with an average full width at half maximum (FWHM) of 9.5 nm and spatial resolution of 1 m. The AISA digital numbers represented reflectance values (times a multiplier) that had been corrected from geometric and radiometric distortions. Five image strips of 10-km length and 1-km swath were used to create a mosaic image, from which a subset of 2.3-km by 10-km was extracted.

The AISA image showed a strong absorption feature around 934 nm (water vapor absorption) and a weaker absorption feature