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Effect of image spatial and spectral characteristics on mapping semi-arid rangeland vegetation using multiple endmember spectral mixture analysis (MESMA)

K.R. Thorp [a,*], A.N. French [a], A. Rango [b]

[a] *USDA-ARS, U.S. Arid Land Agricultural Research Center, 21881 N Cardon Ln, Maricopa, AZ 85138, United States*
[b] *USDA-ARS, Jornada Experimental Range, P.O. Box 30003, MSC 3JER, NMSU, Las Cruces, NM 88003, United States*

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ABSTRACT

Encroachment of invasive shrubs into grassland areas on rangelands in the southwestern United States threatens the viability of livestock production and can severely alter hydrology and biodiversity. Novel remote sensing technologies may provide useful information for monitoring and remediating this threat. The objectives were to investigate multiple endmember spectral mixture analysis (MESMA) as an approach to map rangeland vegetation using hyperspectral remote sensing imagery and to test the sensitivity of MESMA to alternative image spatial resolutions and spectral waveband combinations. Data from two Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) overflights at the Jornada Experimental Range in southwestern New Mexico were used in the analysis. Endmember spectra were selected from a library of ground-based spectral observations collected with a field spectroradiometer. A 4-endmember MESMA was conducted for both AVIRIS images at their native spatial resolutions using 113 10-nm wavebands from 422 to 2339 nm. Additional MESMAs were conducted at 10 multiples of the images' native spatial resolution and for 6 alternative combinations of spectral waveband subregions. Maps of endmember fractional cover for green shrub vegetation, nonphotosynthetic grass vegetation, and bare soil were comparable to an earlier vegetation classification map of Jornada. MESMA fractional cover estimates for the green vegetation endmember were positively correlated with the normalized difference vegetation index (NDVI) with correlation coefficients (r) greater than 0.58. Correlation coefficients between the sum of the green and nonphotosynthetic vegetation endmembers and the cellulose absorption index (CAI) were greater than 0.59. Correlation coefficients between MESMA fractional green vegetation cover and NDVI from independent multispectral images were greater than 0.57. Despite losses in spatial detail at coarser image spatial resolutions, MESMA results for images with spatial resolution degraded by a factor of 10 (~150 m) were similar to aggregated results for MESMA at the native spatial resolution (~15 m). Additionally, MESMA results were shown to be substantially more sensitive to the spectral wavebands used in the analysis as compared to the spatial resolution of the images. Considered together, the MESMA results at Jornada indicated that fine spectral resolution with hyperspectral remote sensing was substantially more important than incremental changes in image spatial scale from 15 m to 150 m.

1. Introduction

Over the past century, rangelands in the northern Chihuahuan Desert have been severely degraded due to livestock overgrazing and other human activities (Hoyt, 2002). Drought and climate change have also played a role (Chehbouni et al., 2000). Several focused studies of vegetation change at the Jornada Experimental Range (Jornada) in southwestern New Mexico have documented the encroachment of invasive shrubs, such as mesquite (*Prosopis glandulosa*), creosote bush (*Larrea tridentata*), and tarbush (*Flourensia cernua*), into areas once dominated by grass. These intrusions have led to severe losses in grassland vegetation at Jornada (Buffington and Herbel, 1965; Gibbens et al., 2005). Unsuccessful efforts to remediate grasslands by shrub removal suggest that shrub invasion leads to soil erosion and hydrologic alterations, which impede the reestablishment of grass species (Rango et al., 2005).

Continued efforts to monitor and remediate these threats to rangeland environments will be bolstered by the availability of remote sensing technologies and the development of novel remote sensing instrumentation and data processing algorithms. Previous approaches using aerial photography at Jornada have been narrowly focused and lacking in spectral information (Rango et al., 2005). Comprehensive, rapid, and repeated viewing of large rangeland areas will require deployment of sensors at high altitude or from orbit. With the advent of airborne hyperspectral remote sensing instrumentation such as AVIRIS (Green et al., 1998), analyses using hyperspectral data to characterize rangeland degradation and monitor vegetation change are increasing (Asner and Heidebrecht, 2002; Asner et al., 2000; Li et al., 2005; Mansour et al., 2012; Yang et al., 2009). Further investigation of

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[*] Corresponding author. Tel.: +1 520 316 6375; fax: +1 520 316 6330.
E-mail address: kelly.thorp@ars.usda.gov (K.R. Thorp).

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these novel remote sensing techniques is required before the technology can deliver on its promise to guide policy development and support long-range planning for better management of rangelands.

The primary advantage of hyperspectral remote sensing over current multispectral techniques is its ability to resolve the reflectance responses of image features with fine spectral detail, usually in hundreds of narrow, contiguous spectral wavebands. Hyperspectral observations of homogeneous vegetation canopies may demonstrate unique responses over certain waveband regions as compared to that for other plant species or soil backgrounds (Thenkabail et al., 2000). In cases where vegetation canopies are not homogeneous or where spatial resolution is too coarse to avoid mixed pixels, spectral mixture analysis can be used to resolve fine scale land surface features. Spectral mixture analysis (SMA) is a hyperspectral data processing approach that quantifies the proportions of land surface features within mixed pixels using knowledge of each feature's pure spectral response or “endmember.”

A major limitation of SMA is that every image pixel is unmixed using the same endmember spectra. This is problematic when a feature is present only in certain portions of the image or when a feature exhibits substantial spectral variation that is not well represented by one endmember spectral observation (Dennison and Roberts, 2003). Multiple endmember spectral mixture analysis (MESMA) addresses these problems by testing multiple combinations of endmembers and endmember spectra for each pixel in the image (Roberts et al., 1998). Thus, MESMA increases the flexibility of simple SMA. As compared to common multispectral approaches, the main advantage of SMA and MESMA is their ability to facilitate remote sensing data analyses using full spectrum information.

Image spatial and spectral resolutions are expected to influence MESMA outcomes. However, the sensitivity of MESMA results to these factors has not been quantified. A better understanding of MESMA performance constraints is informative for the development of novel hyperspectral imaging systems. For example, the National Aeronautics and Space Administration (NASA) is currently developing the Hyperspectral Infrared Imager (HyspIRI) and is planning for the instrument's deployment by satellite (hyspiri.jpl.nasa.gov). HyspIRI will include an imaging spectrometer observing from 380 nm to 2500 nm in 10 nm contiguous bands and a multispectral imager observing from 3 to 12 μm. These instruments will provide images with spatial resolution of 60 m at a nadir view angle. Given these design characteristics, images from other sensors can be used to simulate and evaluate HyspIRI data sets prior to launch. Images from the AVIRIS sensor are useful for evaluations of the HyspIRI imaging spectrometer, because AVIRIS spectral resolution is similar to HyspIRI (aviris.jpl.nasa.gov). Also, the spatial resolution of the AVIRIS sensor, flown at the typical altitude of 20 km, is 4 times finer than that proposed for HyspIRI, which allows for assessments of the effects of HyspIRI's coarser spatial resolution on data analysis.

The first objective was to investigate multiple endmember spectral mixture analysis (MESMA) as an approach to map rangeland vegetation using hyperspectral remote sensing data, such as that currently obtained with AVIRIS and proposed for HyspIRI. The Jornada Experimental Range was the field site used for the analysis. The second objective was to test the sensitivity of MESMA results to degradations in image spatial resolution and to the use of alternative spectral wavebands. The latter objective supports design efforts for the HyspIRI sensor prior to launch.

2. Materials and Methods

2.1. Jornada Experimental Range

The Jornada Experimental Range (Jornada; jornada.nmsu.edu) was established by the United States Department of Agriculture in 1912 to develop effective strategies for management of livestock grazing lands. It is a 783 km^2 semiarid rangeland located on the Jornada del Muerto Plain in the northern part of the Chihuahuan Desert in southwestern New Mexico, roughly 37 km northeast of the city of Las Cruces and 40 km west of the White Sands National Monument (Fig. 1). Similar to the analysis of Jornada vegetation provided by Gibbens et al. (2005), the analysis reported herein focuses on the 582 km^2 Jornada plain west of the San Andres Mountains. Jornada has been a National Science Foundation Long-Term Ecological Research site since 1981. Havstad et al. (2000) provide a detailed description of Jornada and its historical use as a site for evaluation of satellite remote sensing systems, including the JORNEX and PROVE (Privette et al., 2000) experiments.

2.2. Airborne Imaging Spectroscopy

The AVIRIS imaging spectrometer (Green et al., 1998) was used to collect remote sensing images over Jornada on several dates from 1997 to 2002. The present analysis focused on two of those dates: June 15, 2001 and October 9, 2002. The instrument was deployed using an airborne platform flying approximately 20 km above sea level. AVIRIS collected radiometric observations between 380 nm and 2500 nm using 224 unique detectors each with a nominal spectral bandwidth of 10 nm. A whiskbroom scanning mirror with a 12 Hz scanning rate was used to obtain cross-track spatial samples.

Five flight lines were required to obtain full coverage of Jornada on each acquisition date. Preliminary data processing steps, including geometric and radiometric correction, were completed by the AVIRIS Data Facility. Images were georeferenced using a geometric look-up table constructed using data from the navigation equipment aboard the aircraft. Images were also calibrated to spectral radiance.

Further data preprocessing, including atmospheric correction and additional georeferencing, was conducted in-house. Atmospheric correction was accomplished with the Second Simulation of a Satellite Signal in the Solar Spectrum (6S) algorithm (Kotchenova et al., 2006). Based on the cross-track spatial sampling interval of 0.87 milliradians, the viewer zenith angle was calculated at intervals of 25 pixels across the image swath, and 6S parameters for the remaining pixels were interpolated. Since all images were collected along a due north or due south flight line, viewer azimuth angles were set at 90° and 270° for pixels east and west of the flight line, respectively. Solar zenith and azimuth angles were computed at the time and position of the aircraft midway through the data acquisition period for each image (Reda and Andreas, 2004). Atmospheric profiles for pressure, temperature, and water density from ground-level to the sensor-level were obtained from the National Center for Environmental Prediction (NCEP) Reanalysis data set, provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). The data set contains long-term, high-resolution climate information for the North American domain (Mesinger et al., 2006). The NCEP data nearest in time and space to the AVIRIS overflights at Jornada were used to specify the 6S parameters for atmospheric profile. The 6S default “Desert Model” with a visibility of 16 km was used to define the aerosol profile. Spectral conditions were assumed to be monochromatic; 6S was provided the wavelength at the center of each of AVIRIS waveband. Lambertian ground reflectance was assumed. Given the complexity of correcting multiple bands and scenes, a Python script (www.python.org) was developed to conduct 6S simulations and atmospherically correct the AVIRIS images.

Automated methods at the AVIRIS Data Facility provided major help with image geometric corrections. However, additional corrections were needed to properly mosaick the five images on each data collection date. Images were therefore corrected further by selecting ground control points from an orthophoto provided by the United States Geological Survey (USGS). Approximately 50 points per image were required for improving the image registration. Images were then georegistered using polynominal warping