Characterization of land degradation in central Argentina with hyperspectral AVIRIS and EO-1 data

HUETE Alfredo (1), GAO Xiang (1), KIM Ho Jin (1), MIURA Tomoaki (1), BORGHI Carlos (2) and Ricardo OJEDA (2)

(1) University of Arizona, Tucson, Arizona, USA
(2) CRICYT, Mendoza, Argentina

Abstract

Ground, air- and spaceborne hyperspectral data sets were collected over several land cover types, representative of various stages of land degradation in the Mendoza region of Argentina. EO-1 Hyperion satellite imagery, airborne AVIRIS imagery, and field-measured ASD spectroradiometer data were acquired over the protected Ñacuñán Reserve composed of floristically diverse vegetation communities, including mesquite shrub (algorrobol), sand-dune (medanal), creosotebush (jarillal), and severely degraded (peladal) sites. Field-based biophysical measurements included soil, litter, vegetation cover, and leaf area index (LAI) measurements. The field data were co-registered with AVIRIS and Hyperion imagery for a landscape analysis of land degradation. We investigated various remote sensing based degradation indicators including albedo, spectral vegetation indices, pixel variance, first derivative analysis of spectral signatures, and soil, litter, and vegetation mixture component analysis. Our goal was to assess the utility of hyperspectral data in discriminating the gradient of land conversion vegetation types at various stages of degradation. Spectral mixture modeling was utilized to assess the amounts and structural properties of the various canopy components and to independently assess the soil and vegetation components in characterizing land degradation. We were able to distinguish the stages of land conversion through both spectrally decomposed soil and vegetation components. However, we found soil optical parameters to be more useful than vegetation spectral measures in characterizing land degradation. Hyperspectral data were found to contain more information on soil and vegetation properties than conventional spectral vegetation indices and thus offer more useful information for the identification characterization of land degraded areas.

Keywords: remote sensing, land degradation, hyperspectral, mixture models

Introduction

Soil degradation and desertification are natural processes of aging that are both global and gradual, and aggravated by human activity. Land and soil degradation are major environmental concerns impacting several critical environmental issues such as food security, diminishing quality and quantity of fresh water resources, preservation of natural resources, loss of biodiversity, and global climate change. Land degradation is responsible for soil erosion and can eventually lead to desertification. The International Convention to Combat Desertification (CCD) defines desertification as “land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors,
including climate variations and human activity”. The resulting loss of soil cover, the loss of genetic diversity, the physical and chemical degradation of soils, and sedimentation of river basins and dams creates major environmental constraints for sustainable development. Desertification is a major socio-ecological problem worldwide.

General information and data regarding the degree and extent of soil degradation and the resulting impacts are poorly understood. Effective land degradation monitoring and detection programs have been hampered by the lack of a comprehensive set of guidelines for survey, assessment, and monitoring of land degradation, including early warning indicators. Satellite remote sensing with its temporal and synoptic view, has been successfully used as a starting point in the monitoring and control of desertification (Robinove et al., 1981). Space-based observations offer the opportunity of monitoring and assessing changes in both soil and vegetation properties associated with land degradation such as soil erosion, salinization, and changes in vegetative land cover. Remote sensing provides a quantifiable and replicable technique to assess desertification under a unified methodology at regional and global scales. Remote sensing can contribute with the following objectives; (1) generate information from satellite imagery for analysis; (2) establish quantitative methods for evaluating desertification with well-defined indices; and (3) application of satellite techniques for mapping and monitoring.

There are many indicators and early warning signals of land degradation, which lend themselves to remote sensing-based monitoring. These include (1) loss of vegetative cover; (2) wind and water erosion; (3) soil salinization; (4) soil structure deterioration; (5) less soil moisture; (6) increases in albedo; (7) higher land surface temperatures; and (8) land cover type changes. Otterman (1977) noted sharp increases in albedo in Landsat MSS imagery due to anthropogenic effects with brightening denoting land degradation. Aguiar et al. (1998) produced maps of desertification in Patagonia with NOAA-AVHRR and Landsat MSS. Their methodology included recording data on degradation of vegetative cover and of soil water erosion, wind erosion, soil crusting and compaction, and salinization/alkalinization. Pickup and Nelson (1984) showed that changes in the variance of pixel subareas in Australia could be the most sensitive indicator of landscape instability, with an increase in variance indicating erosion and a decrease in variance indicating the possibility of deposition.

Schlesinger et al. (1990) similarly showed indicators of soil erosion and land degradation were the loss of vegetative cover and spatial variation of soil spectral properties owing to the loss of topsoil and exposure of subsoil layers (at Jornada Experimental Range in New Mexico). As erosion proceeds, more of the parent material mineralogies and spectral properties become evident while the optical properties of the organic rich upper layers become less pronounced. The undisturbed, well-developed soil and the underlying parent material represent the two endpoints from which the various degrees of soil erosion and land degradation can be assessed. These characteristics can be monitored with satellite imagery, using spectral indices and mixture models.

The Earth Orbiter 1 (EO-1) was launched in November 2000 as part of NASA’s New Millennium program that focuses on new, more cost effective technologies for Earth observation. EO-1 includes the hyperspectral Hyperion sensor, a pushbroom
sensor providing 220, 10 nm bands covering the spectrum from 400 to 2500 nm. Hyperspectral remote sensing has improved the feasibility of unambiguously identifying numerous soil and vegetation absorption features, related to mineralogy, liquid water, chlorophyll, cellulose, and lignin contents. Various field campaigns were recently conducted in Australia and Argentina in early 2001, in order to assess the instrument performance and science capability of the EO-1 sensor in a variety of applications, including biogeochemical studies, leaf water content, land degradation, land cover conversions, fuelwood assessment, and soil and vegetation mapping (Smith et al., 1990; Adams et al., 1995). In this study we attempt to fully characterize a set of natural and altered land cover sites in order to determine the potential hyperspectral satellite imaging for land cover change, ecology, and land degradation studies. We investigate hyperspectral measures and indices for assessments of degradation and land health (early warning indicators).

**Materials and Methods**

The Ñacuñan Ecological Reserve is located in the province of Mendoza and is characterized by open forests of mesquite (*Prosopis* spp.) and creosotebush (*Larrea divaricata* and *L. cuneifolia*), locally known as bosques de algarrobos and jarillales, respectively. The Nacuñan Reserve was designated in 1986 and comprises an area of 12,271 ha located in a warm semi desert shrubland ecosystem (34°02'S; 67°54'W). It is at a mean altitude of 540 m with an average annual temperature of 15.8°C and 200 mm annual precipitation. It is administered by the Instituto Argentino de Investigaciones de las Zonas Aridas (IADIZA) and is a designated UNESCO Biosphere Reserve.

The main vegetation communities within and outside the Reserve are readily seen with a 4-meter resolution IKONOS image acquired in June 2001 (dry, cold season) (Figure 1).

![Image of vegetation communities](image_url)

**Figure 1**
The main vegetation formations include (1) a medanal community consisting of both mesquite and creosotebush species and characterized by active sand dune formations; (2) a jarillal community made up of mostly creosotebush appearing dark in Figure 1; (3) an algarrobal community with mixed mesquite-creosotebush and appears pinkish in color due to the vigorous mesquite tree leaves; and (4) a peladal community which is degraded and has stunted creosotebush and appears very bright in Figure 1. The degraded areas outside the Reserve consisted mostly of the sand-dune areas (medanal communities) and playa or peladal sites.

Field measurements

Radiometric and biophysical field measurements were conducted inside and outside the Ñacuñan Reserve over restored and degraded areas. An ASD FieldSpec radiometer was used to measure surface optical components over a spectral range from 370 nm to 1050 nm. We conducted 100 m yoke-based transects at all the study sites with the ASD radiometer. We also made ‘pure’ spectral signature measurements of the green vegetation, soil, and non-photosynthetic vegetation (NPV) components at each site. We made simultaneous measurements of soil and vegetation biophysical/structural properties, including leaf area index (LAI) and fractional component covers along the 100 m transects. All ASD spectra were converted to reflectance values with the use of a standard reference, Spectralon panel.

Aviris and hyperion imagery

Low level Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) flights were made at the Ñacuñan Reserve on February 15, 2001. The AVIRIS imaging spectrometer operates in the 400 to 2450 nm region collecting 224 spectral bands with a nominal 10 nm spectral response function. AVIRIS flew at an altitude of 4 km yielding 4 m pixels. The EO-1 Hyperion sensor collected images at the Ñacuñan and Reserves on February 16th. All hyperspectral imagery were corrected for atmosphere and converted to surface reflectances with the aid of an atmosphere correction program, ATREM, and calibration ground control points. The ASD spectral measurements from the ground were registered to the AVIRIS image with the help of GPS data.

Degradation indicators

We computed various vegetation indices, including the normalized difference vegetation index (NDVI), the soil-adjusted vegetation index (SAVI), and the enhanced vegetation index (EVI). The NDVI has problem with soil background and responds to both changes in soil signal and to changes in vegetation and thus an effective index is needed which does not respond to the soil background, hence the SAVI and EVI.

We first used principal components analysis to understand the spectral content of the AVIRIS and Hyperion imagery. We assessed the dimensionality of the data sets and investigated the unique spectral features present in the hyperspectral imagery. We performed linear spectral mixture analyses to decompose the optical data into several spectral features, including a soil sensitive measure, a non-photosynthetic vegetation signal (wood/ litter), and a vegetation sensitive measure to assess how land degradation can best be detected and monitored using this technique. Spectral mixture modeling can be used on hyperspectral data sets to un-mix the canopy signal, identify its relevant components and assess their biophysical quantities.
Results and Discussion

Analysis of the field-based ASD spectral signatures revealed that the severely degraded and denuded playa sites had the highest overall reflectances. The peladal sites contained spectral signatures of intermediate brightness with very little structure indicative of green vegetation. The sand-dune medanal site had the darkest reflectances and showed a weak vegetation signal between the red and NIR portions of the spectrum. Only the more mesquite sites resulted in a stronger vegetation signature with distinct red absorption and NIR plateau regions. We utilized these field measured spectral signatures to calibrate the hyperspectral imagery following atmosphere correction. We achieved a good correspondence between the ASD spectral signatures and the AVIRIS derived spectral signatures.

Principal components analysis of the >200 spectral bands in the AVIRIS imagery revealed that there were four significant components. The eigenspectra of these four components are plotted in Figure 2 along with the first three component images. The eigenspectra reveal unique spectral features in the short-wave infrared region (SWIR) as well as in the visible portions of the spectrum. Normally the NPV features show up in the SWIR region, so this revealed that a significant amount of spectral variation at this site was associated with non-photosynthetic vegetation components such as woody shrub material. The first component image is similar to an average or ‘brightness’ image of the area. The fenced boundaries of the northwest section of the Nakunan Reserve show up quite clearly with the inside of the Reserve slightly darker in appearance from outside the Reserve. The darker patterns of the creosotebush vegetation communities and lighter mesquite areas are clearly delineated. The very bright and degraded peladal areas also show up (Figure 2).

![Figure 2](image)

Figure 2

The second principal component (PC2) is a ‘vegetation’ related component as the second eigenspectra has the shape of a green vegetation spectral signature. The peladal areas are very dark indicative of near zero vegetation amounts. The fenced boundary of the Nakunan Reserve, however, is not so distinct indicating that there are no significant differences in vegetation amounts between the inside and immediate outside portions of the Reserve. There is more variations associated with the creosote and mesquite shrub
communities with the ‘darker colored’ creosote showing up as the highest amounts of vegetation (Figure 2, PC2). Thus, aside from the extremely degraded peladal sites, there is more variation in canopy structural differences than in degradation classes. The third principal component is not readily interpretable.

We then proceeded with a spectral mixture model of the AVIRIS data (Figure 3) using the pure ‘endmember’ spectral signatures representing soil, vegetation (mesquite), NPV (gray grass), and shade. In the mixture model case, the final results are calibrated to these pure spectral signatures enabling easier interpretation of the mixture loadings images as well as allowing quantitative retrievals of the amounts of each pure component present in each pixel. The resulting vegetation, soil, NPV, and shade loadings images are shown in Figure 3. The ‘green vegetation’ loadings image show no significant differences between the Reserve interior and immediate outside surroundings. There is also less variation encountered among the vegetation shrub communities. The peladal areas do show up as nearly denuded, without vegetation. There is also some very bright (highly vegetated) areas adjacent to the peladal areas, which were cottonwood trees present near the water holding areas.

The soils component image (Figure 3) reveal much more information on land surface characteristics in this area of active desertification. The inside of the Nacuñan Reserve is significantly darker than the outside surroundings, suggesting darker soils with less disturbance and less removal of the organic rich topsoil. The peladal areas are extremely bright indicative of strong soil degradation. Within the Reserve, the creosotebush communities has darker ‘soil’ signals. The soil signal over mesquite was brighter but still darker than in the mesquite areas outside the Reserve. The NPV image reveal less variation. NPV values are extremely low in the peladal areas and appear highest in the mesquite vegetation communities.

A crossplot of the NPV and vegetation loadings (Figure 4) reveal that the quantity of NPV increases positively with increasing levels of vegetation. The NPV increases from the peladal sites to the medanal (sand-dune sites) community, the creosotebush, and finally the mesquite community. However, there is a second axis of variation such that within a given vegetation community, there is an inverse relationship between NPV and amount of green vegetation. This is basically stating that for a fixed shrub community the vegetation is either foliated (green leaves) or it is defoliated exposing the woody, NPV signal. The shade vs. vegetation crossplot (Figure 4) reveal information about the structural characteristics of the vegetation. As the amount of vegetation increases, the amount of shade present in a pixel also increases, which is expected in

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semiarid regions since it is the vegetation that casts the shade. The slope of this relationship is a function of the type of canopy structure with mesquite showing the most sensitivity (steepest slope) and the creosotebush and medanal canopies having lower slopes and the peladal sites barely showing any slope (Figure 4).

Figure 4

Discussion

The use of satellite observations to manage the soil resource and monitor land degradation processes has a promising future, particularly with the recent launch of improved hyperspectral sensor systems. Such systems, with over 200 channels have great potential in extracting soil and vegetation biogeochemical component information. As shown in this study, we are able to characterize the land surface in terms of soil properties, NPV properties, and green vegetation amount and type. These are sub-pixel assessments of the multiple parameters, which become a powerful monitoring tool when combined with multitemporal remote sensing sensor systems.

We found that land degradation was best characterized by the soil and NPV component information derived from spectral mixture modeling. Soil spectral signatures were significantly different in the land converted areas. Although the separated vegetation signal did show some variance, it was relatively minor when compared with the other component images. When the component images were combined, as in the loadings crossplots in Figure 4, then one was able to more efficiently and accurately characterize the landscape with respect to degraded areas as well as natural vegetation communities. When this type of remotely-sensed information is combined with GIS and process models, then desertification can be quantitatively evaluated and monitored. In this way, the different processes that contribute to desertification (erosion, salinization, denuding of soil, overgrazing, water resources) can be assessed.

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References


