MULTIPLE ENDMEMBER SPECTRAL MIXTURE ANALYSIS:

APPLICATION TO AN ARID/SEMI-ARID LANDSCAPE

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1. INTRODUCTION

As the Earth's human population increases and once-fertile areas become less so, human activities are bound to spread into areas that once were considered barren and unworkable, namely our planet's arid and semi-arid regions. Worldwide, this process has begun. As a result, these fragile areas are being put under stresses which are leading to severe landscape damage and hence, a decrease in usefulness to humans. This process of "desertification" is already widespread, and although many people frequently consider desertification to be a problem unique to arid and semi-arid Africa, it is in fact occurring on all continents except Antarctica.

Desertification is actually a complex suite of phenomena which occur in arid and semi-arid environments which can be triggered by human land use, interannual climate variability or long-term climate change. Many interrelated processes on sub-canopy to regional spatial scales are included, but the dominant form of desertification in the southwestern US is the conversion of grasslands to shrublands (Sears, 1935; Buffington and Herbel, 1965; Mabbutt and Floret, 1980). The processes involved frequently occur as "runaway" phenomena which are not reversible or remediable on human timescales for reasonable cost (Schlesinger *et al.*, 1990). As a result, monitoring of arid regions is critical in any attempt to short-circuit these land degradation processes.

Remote monitoring using current or anticipated satellite remote sensing is the most time- and cost-efficient way to proceed with arid region monitoring in the future. Unfortunately, interpretation of remote sensing data from arid regions is particularly difficult. Three factors are thought to contribute to this. First, arid and semi-arid regions are often characterized by large soil background in many cases swamping out the spectral contribution of plants (Huete *et al.*, 1985; Huete and Jackson, 1988; Smith *et al.* 1990; Escafadel and Huete, 1991). Second, light rays reaching sensors from desert plants are often polluted by additional interactions with desert soils (Huete, 1988; Ray and Murray, 1996). Finally, due to evolutionary adaptations to the harsh desert environment, desert plants are spectrally dissimilar to their humid counterparts lacking in many cases a strong red edge, exhibiting reduced leaf absorption in the visible, and displaying strong wax absorptions around 1720 nm (Ehleringer, 1981; Ray, 1995).

Many of the early applications of remote sensing to arid and semi-arid regions suggest that present remote sensing techniques, including most brightness and greenness indices, are susceptible to over- or underestimation of vegetation cover simply due to variations in soil color and low vegetation cover (Huete *et al.*, 1985; Huete and Jackson, 1987; Huete and Jackson, 1988; Escafadel and Huete, 1991; Pickup *et al*, 1993) although Musick (1984) found a correlation between total vegetation cover and Landsat MSS band 5 brightness. None of theses studies were able to accurately and reliably discern shrubs from grasses in arid and semi-arid environments which is probably the most important means by which to identify desertification (Schlesinger *et al.*, 1990). Later work by Franklin *et al.* (1993) and Duncan *et al.* (1993) using SPOT wavebands and greenness and brightness indices found these indices to be sensitive to vegetation type as well as cover. High variance in these studies, however, suggests that even in cases where landscape components were determined to be significantly different, it may not be possible to accurately retrieve the contribution of these components to a spatially-averaged reflectance measurements. This is presumably due to the low spectral resolution of the SPOT wavebands and the effect of nonlinear mixing under low cover conditions as well as the typically high spectral variability found in desert plants.

Despite the lackluster performance of remote sensing in arid regions, there are have been a few studies which suggest that there is potential for doing accurate and reliable remote sensing in arid and semi-arid regions. Smith *et al.* (1990) applied a mixing model employing laboratory and field spectra to Landsat TM data from the Owens Valley indicating that mixture modeling can facilitate mapping and monitoring of sparse vegetation cover. Roberts *et al.* (1993) have used linear mixture analysis of AVIRIS data to map green vegetation, nonphotosynthetic vegetation (NPV), and soils at the Jasper Ridge Biological Preserve, CA. It is a natural next step, therefore, to apply spectral mixture analysis to arid and semi-arid regions in the hope that this will overcome previous difficulties in accurate and reliable landscape assessment by remote sensing in these areas. The purpose of this study is to determine if the multiple endmember spectral mixture analysis approach will provide an accurate and reliable means to characterize arid and semi-arid region vegetation and soils from AVIRIS data. The ultimate goal of this work is to develop tools for remote sensing of arid regions which make the best use of current and near-future remote sensing technology to monitor these environments.

2. METHOD

2.1 Study Site Description

This study was conducted at the Jornada Long Term Ecological Research (LTER) site 23 miles northeast of Las Cruces, NM in the Chihuahuan Desert ecosystem. It is located on the Jornada del Muerto plain, which is bounded by the San Andres Mountains on the east and by the Rio Grande Valley and the Fra Cristobal-Caballo Mountain complex on the west. Elevation varies from 3,900 to 4,500 feet. The Jornada Plain consists of unconsolidated Pleistocene detritus. This alluvial fill from the nearby mountains is 300 feet thick in places and the aggradation process is still active. Coarser materials are found near foothills along the eastern part of the study area. The topography of the study area consists of gently rolling to nearly level uplands, interspersed with swales and old lake beds (Buffington and Herbel, 1965).

The climate of the area is characterized by cold winters and hot summers and displays a bimodal precipitation distribution. Winter precipitation usually occurs as low-intensity rains or occasionally as snow and contributes to the greening of shrub species in the basin in the early spring. Summer monsoonal precipitation, usually in the form of patchy but intense afternoon thunderstorms, is responsible for the late-summer greening of grasses. The average annual precipitation between 1915 and 1962 in the basin was 23.1 cm, with 52% falling between July 1 and September 30 (Paulsen and Ares, 1962). The average maximum temperature is highest in June when it averages 36°C and lowest in January when it averages 13°C (Buffington and Herbel, 1965)

The principal grass species in the study area are burrograss (*Scleropogon brevifolius*), several species of *Aristida*, and tobosa grass (*Hilaria mutica*) while major shrubs are creosote (*Larrea tridentata*), mesquite (*Prosopis glandulosa*), and tarbush (*Florensia cernua*). Soils in the basin are quite complex but generally range from clay loams to loamy fine sands with some areas being sandy or gravelly (Soil Conservation Service, 1980).

2.2 Image Acquisition and Processing

AVIRIS data were acquired over the Jornada Basin on May 27, 1997. After they were acquired, data were radiometrically corrected at the AVIRIS data facility. Apparent surface reflectance was retrieved using a technique developed by Green *et al.* (1993; 1996; Roberts *et al.* 1997a). This technique uses MODTRAN 3.5 to generate look-up tables for path radiance and reflected radiance for water vapor at a range of values for a specified date, time, location, meteorological visibility, and surface elevation. Modeled radiance is fitted to the 940 nm atmospheric water band of measured upwelling radiance by using a nonlinear least-squares-fitting routine on a pixel-by-pixel basis. Apparent surface reflectance is calculated for each pixel by modeling total upwelling radiance at the sensor as the sum of the path radiance and atmospherically-attenuated reflected surface radiance.

2.3 Multiple Endmember Spectral Mixture Analysis

Spectral mixture analysis (SMA) is based on the assumption that the reflectance spectrum derived from an air- or spaceborne sensor can be deconvoluted into a linear mixture of the spectra of ground components, frequently called spectral endmembers. The best-fit weighting coefficients, which must sum to one, of each ground component spectrum are interpreted as the relative area occupied by each component in a pixel. Multiple endmember spectral mixture analysis (MESMA) is simply a SMA approach in which many possible mixture models are analyzed in order to produce the best fit (Gardner, 1997; Roberts *et al.*, 1997b; Painter *et al.* 1997). In the MESMA approach, a "spectral library" is defined which contains spectra, convolved to the 224 AVIRIS bands, of plausible ground components. A set of mixture models with n ($n \geq 2$) endmembers from the library is defined, with shade always present as one endmember in the model. The weighting coefficients (fractions) for each model and each pixel are determined such that the linear combination of the endmember spectra produces the lowest RMS error when compared to the apparent surface reflectance for the pixel. Weighting coefficients are constrained to be between zero and one, and a valid fit is restricted to a maximum preset RMS error. Models which meet these constraints are recorded, which typically yields several possible models for each pixel. As an optional final step, the one model for each pixel with the lowest RMS can be identified. It is these best-fit models which are discussed below.

This approach requires an extensive library of field or image spectra where each plausible ground component is represented at least once. Including more than one spectrum of a ground component allows for the considerable spectral variability often found in desert vegetation, thus overcoming a difficulty identified by Franklin *et al.* (1993) of doing remote sensing in arid regions.

2.4 Methods Used in This Study

In this study two-, three-, and four-endmember models were run on the apparent surface reflectance retrieval from an AVIRIS scene which includes the headquarters of the Jornada LTER site (flight 970527 run 2, scene 6).

Warren and Hutchinson (1984) correctly suggested that the phenological stages of arid and semi-arid region plants would affect their spectral characteristics. This "spectral phenology" is a further complication of arid region remote sensing and suggests that SMA will be most effective when field spectra taken at the same time as the acquisition of remote sensing data are used in mixture models. Field spectra collected in the Jornada LTER site during May 24-25, 1997 were incorporated into the spectral library in this study in order to make as direct an identification of landscape components as possible. Field spectra were collected from 350 nm to 2500 nm using an ASD Full Range portable spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO) on loan from the Jet Propulsion Laboratory. With a 100% reflective Spectralon panel, spectra can be displayed and recorded in real-time as reflectance.

A total of 36 field spectra were chosen to be included in the spectral library for this study. This includes spectra of nine soils, nine grasses (three species), seven creosote, four tarbush, and seven mesquite. Representative spectra are shown in Figure 1. Soil spectra were given the names of the sites at which they were collected. Four soil spectra that appeared to model soils in the basin are: *M-rab*, a dark red loamy fine sand soil of aeolian origin from a mesquite duneland, *P-tabo*, a clay loam from a gypsiferous playa, and *T-east* and *G-basn*, clay loam to fine sandy loam soils found on basin floors and toe slopes of fans (Soil Conservation Service, 1980). Grasses at this time of the year were by and large senesced. Spectra used in three- and four-endmember models were chosen to minimize computation time and to maximize spectral variability using the method outlined by Gardner (1997). In this library analysis, each spectrum in the spectral library is modeled by every other spectrum in the library coupled with shade and constrained by the constraints that will be used in the final analysis. This allows spectra to be compared to one another, and redundant or unique spectra to be identified. Spectra were chosen which 1) modeled other spectra of the same type, 2) were not modeled by other spectra of the same type, and 3) were not confused with spectra of other types.

For the two-endmember models, the entire 36-member spectral library was used in MESMA modeling. For the three-endmember models, all soil + grass + shade, soil + shrub + shade, grass + shrub + shade combinations of a reduced library (spectra of seven shrubs, six grasses, and six soils) were used, resulting in a total of 144 different models. Finally, for the four-endmember models, four soil spectra, six grass spectra, and six shrub spectra were used to define a total of 146 soil + grass + shrub + shade models. Each of the models was run twice: once with a maximum RMS threshold of 2.5% and once with a maximum RMS threshold of 2.0%.

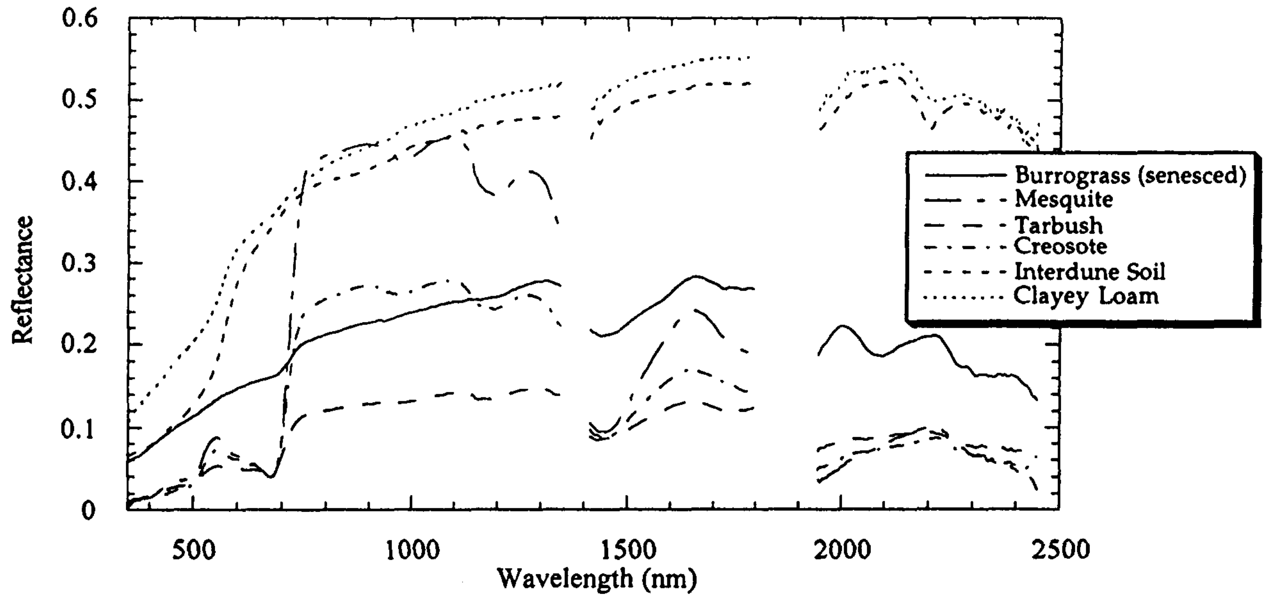

Figure 1. Representative spectra used in MESMA of AVIRIS image

3. RESULTS AND DISCUSSION

3.1 Two-Endmember Models

Two endmembers modeled only 24% of the AVIRIS scene within the 2.5% RMS constraints. The only endmembers that successfully modeled the image were soils, mainly *T-east* and *P-tabo*. This implies primarily that the first-order signal in the image is soil, which is to be expected in an arid environment and indeed confirms other authors' results that soil is the major spectral contributor to remote sensing data in arid and semi-arid regions (Huete *et al.*, 1985; Huete and Jackson, 1988; Smith *et al.*, 1990; Escafadel and Huete, 1991). This result also suggests that since the soil signal is so strong, it might be very difficult to get much information about vegetation in the scene.

Although a quarter of the scene was modeled using just soil and shade, examinations on the ground suggest there are very few areas in this region that are pure soil. Virtually all of the pixels probably contain some vegetation. Clearly, two-endmember models are inadequate for use in this environment where soil is the major, but not only, contributor to pixel-wide spectral averages. Reducing the maximum RMS constrain to 2.0% efficiently eliminated the two-endmember models from consideration, with less than 2% of the entire scene meeting the constraints. This is further evidence that two-endmember models can not accurately be used to model reflectance in this scene.

3.2 Three-Endmember Models

Figure 2 is a map of fencelines within the AVIRIS scene taken from ground data acquired from Barbara Nolen at the Jornada LTER office, New Mexico State University. This map is at the same scale as all Figure 3 images and is to be used as a geographical comparison. Features of note in this image are the square exclosure on the western side of the map, the southwest-northeast trending fenceline southeast of the exclosure, and the Jornada LTER Headquarters north of the exclosure.

The three-endmember models were divided into 3 categories: soil + shrub + shade, soil + grass + shade, and shrub + grass + shade. With an RMS constraint of 2.5%, 90% of the image was modeled, whereas a 2.0% RMS constraint reduced this fraction to 30%. The shrub + grass + shade category modeled virtually none of the image, a testament to the strength of the soil signal and its importance in any SMA models for this environment. Figure 3b shows pixels that were best modeled by soil + shrub + shade as gray, and those best modeled by soil +

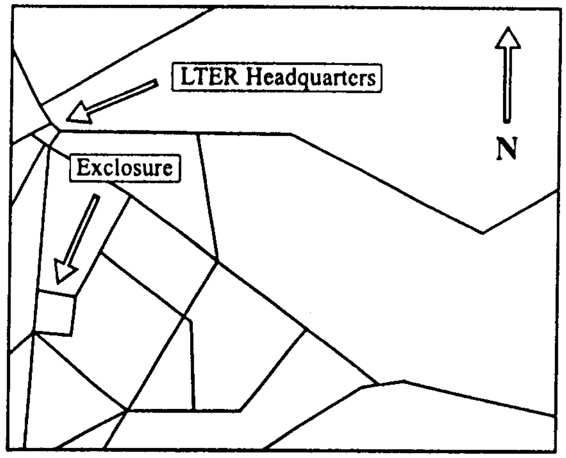

Figure 2. Fencelines in AVIRIS scene used in this study.

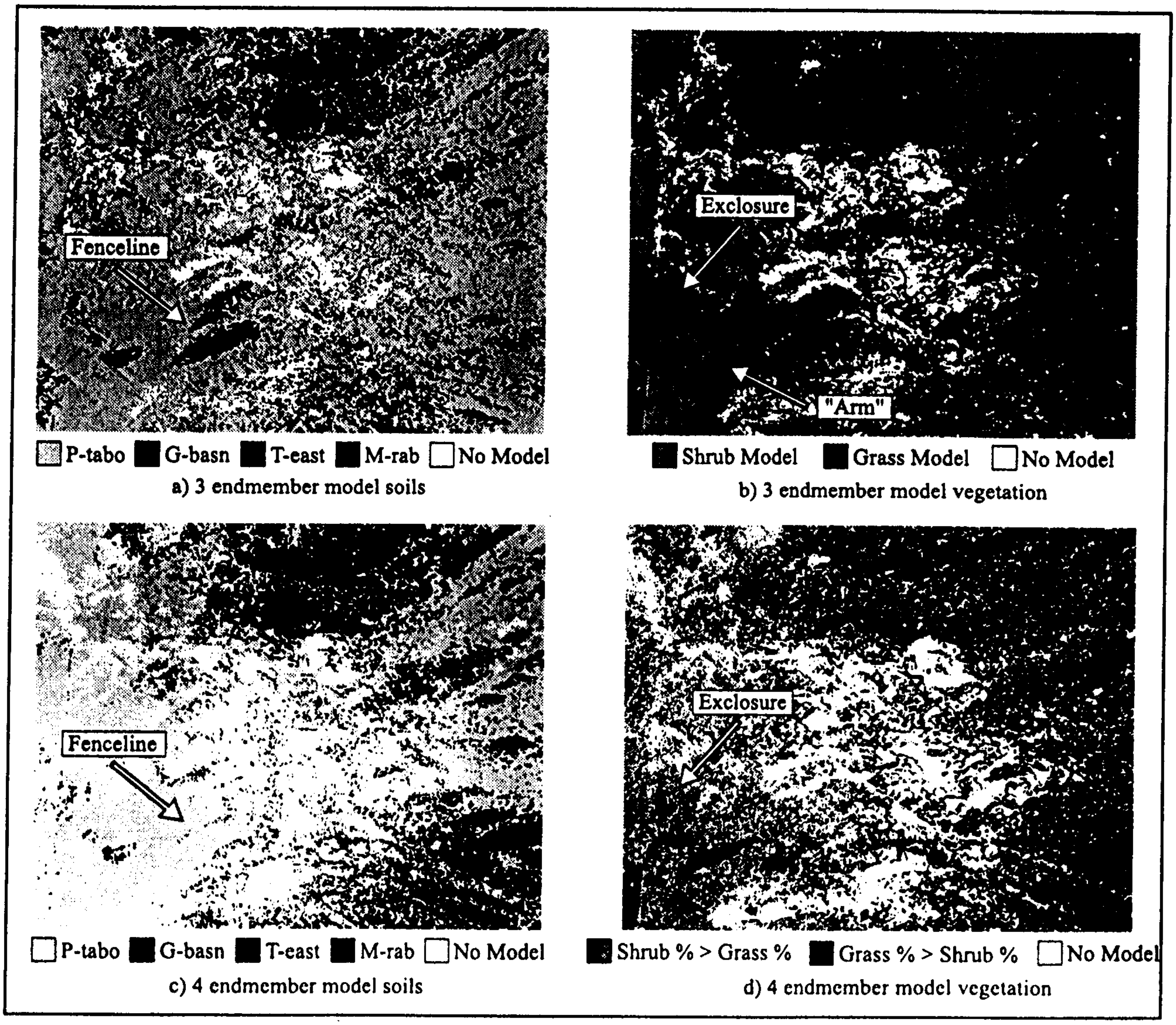

Figure 3. Results of MESMA for 3- and 4-endmember models with maximum RMS of 2.5%.

grass + shade as black. Most of the scene was modeled by soil + shrub + shade, giving the impression that shrubs dominate the environment. The most successful shrub spectra in the three-endmember models were of creosote and tarbush. This result is certainly reasonable given preliminary examination of the environment which suggests that these shrubs are dominant in this area. A significant part of the image was not modeled by any three-endmember model at the chosen RMS constraints. This suggests that a prominent and unique endmember is missing from the spectral library, which corresponds to some obvious bright features in apparent surface reflectance found in the central part of the scene (not shown).

The areas where the grass models are chosen imply that the three-endmember approach is able to capture some of the true vegetative variability in the scene. Most obviously, the square exclosure in Figure 3b and the "arm" adjacent to it are clearly visible in the image as a sea of grass models amidst an ocean of shrub models. This indicates a clear spectral change across fencelines which may by due to a real change in vegetation. Preliminary ground observations suggest that these areas are indeed dominated by grass.

Figure 3a shows the four soils which dominate the three-endmember results. *P-tabo* is the most prominent soil, spanning the entire image, and accounting for most of the soil in the left side of the image. *M-rab* shows several contiguous features, especially a large portion of the top of the image and a long linear feature across the middle of the image. It also appears in the exclosure and the "arm". *G-basn* is spread across the image, and has a spurious look to it, since it is quite fragmented and frequently borders unmodeled portions of the image. *T-east* shows up in the same regions as *M-rab*, but with much less frequency.

The frequency of *P-tabo* in successful three-endmember models is not geologically sensible: *P-tabo* is a gypsiferous playa soil but the areas best modeled by it are not playas. On the other hand, areas best modeled by *M-rab* are sensible: *M-rab* is an interdune soil and areas best modeled by it are aligned with the dominant southwest-northeast trending wind direction in the basin and also correspond to areas mapped as highly susceptible to wind erosion (Soil Conservation Service, 1980). Few pixels are best modeled by *T-east,* which was collected just off the southwestern edge of the scene. This might be interpreted as an erroneous result. However, the Soil Conservation Service soil map (1980) of the basin does place a boundary between the southwest corner of this image and the *T-east* site in both soil type and texture, suggesting that despite its proximity, the *T-east* soil type is not present in the scene.

One geographical feature in particular stands out in the image to suggest that three-endmember models may not be optimal everywhere in an arid environment: the change of soil model across the fenceline in Figure 3a (cf. Figure 2 for fencelines). Although there are means by which a soil may change across a fenceline, this is unlikely in this case. More likely is a change in vegetation, from grass-dominated to shrub-dominated, across the fenceline due to differential livestock grazing. Since only three endmembers are being used for these models, however, this change in vegetation can't be modeled explicitly, and the difference appears as a change in the soil endmember. This fenceline soil feature can be expected to disappear in the four-endmember models.

Despite the problems with the three-endmember models mentioned above, these results suggest that MESMA may have some success in modeling apparent surface reflectance in arid and semi-arid regions. The fact that grasses are modeled in areas known to be grass dominated-- the exclosure and the "arm"-- as well as the spatial contiguity of the modeled endmembers suggests that MESMA is responding to real spectral variation and may be capable of accurately and reliably modeling soils and vegetation in arid and semi-arid regions. Nonetheless, it is clear that four-endmember models may be required under certain circumstances to deconvolute soils and plant signatures.

3.3 Four-Endmember Models

In this arid region of New Mexico, there are two basic vegetation types: shrubs and grasses. Since the two- and three-endmember modes have shown that soil is the dominant signal in the image, a soil endmember must be included in any mixture model in this region. Thus, to capture the two vegetation types, four-endmembers will often be needed-- soil, shrub, grass, and shade. Since four soils dominated the three-endmember models, these soil spectra were combined with six grass spectra and six shrub spectra to define 146 soil + grass + shrub + shade four-endmember models. With an RMS constraint of 2.5% the four-endmember models fitted 80% of the image while at 2.0% RMS, 34% of the image was modeled. A significant part of the image was not modeled by any four-endmember model at the chosen RMS constraints. These unmodeled areas correspond to the same areas in the three-endmember models that were unmodeled, further indicating that a prominent and unique endmember is missing from the spectral library. The fact that more pixels were modeled at a maximum RMS of 2.5% in the three-endmember models instead of the four-endmember models is likely due to the significant reduction in the size of the spectral library which was needed to make MESMA computation time reasonable.

Displaying pixels with a greater fraction of grass than shrubs and vice-versa in Figure 3d gives the impression that there is much more grass in the region than implied by the three-endmember models. Preliminary ground observations indicate that this is probably the case. Again, forcing only one vegetation endmember on an environment with two distinct vegetation types may be causing erroneous results. The exclosure and the "arm" are still apparent, although the contrast at the fencelines isn't as great as it was in the three-endmember vegetation image (Figure 3b). As hypothesized, the questionable change in soil type across the fenceline noted in Figure 3a has disappeared in Figure 3c, and Figure 3d does suggest that a change in vegetation across this fenceline may be responsible for the apparent soil change noted in the three-endmember results.

Unfortunately, *P-tabo* shows up in the four-endmember results just as it did in the three-endmember results. Once again, this is probably a spurious result. The greater spatial contiguity of the areas mapped as *P-tabo* may suggest, nonetheless, that the four-endmember model really is more successful at disentangling soil from vegetation contributions to apparent surface reflectance. Loss of *M-rab* as the best fit soil in the southeastern portion of the image may also be erroneous.

4. CONCLUSIONS

It was the purpose of this study to determine if the MESMA approach can provide an accurate and reliable means to characterize arid and semi-arid region vegetation and soils from AVIRIS data. The results presented here indicate that MESMA can successfully capture some of the most important landscape features, such as shrub-to-grass ratios, that are relevant for desertification monitoring. Two-endmember models are inadequate for mixture modeling of arid and semi-arid environments. Although MESMA can be forced to model AVIRIS data from these areas using only two-endmembers, these results are not convincing. The fact that two endmember models fail to characterize a significant portion of the image indicates the MESMA is responding correctly to landscape structure. Application of three-endmember models indicate that these models might introduce some errors into the results due to the fact that there is an inadequate amount of variation in the vegetation endmembers to capture real variation on the ground. Four-endmember models provide enough flexibility to account for some of the complexity of this arid environment but may not be applicable everywhere. It is clear from our results that a combination of three- and four-endmember models will be required to apply MESMA accurately and reliably to arid and semi-arid regions. Given the fact that the same areas were modeled with both three- and four-endmembers, the criterion for this choice in arid regions can not be minimum RMS as suggested by Painter *et al.* (1997) for other environments. A new method must be found, and might take advantage of the spectral phenology encountered in arid and semi-arid regions.

5. FUTURE RESEARCH

Although the results of this study are promising, there are some sources of error which must be addressed before this research can proceed further. First and most importantly, the reflectance inversion used in this work has suffered due to the fact that modeled reflectance was not adjusted to a known target reflectance of any one pixel in the scene. This procedure allows refinement of all apparent surface reflectance spectra in the scene and may greatly improve mixture modeling. There are few targets in this study area which are homogenous enough to use for this refinement, but one must be found in order to proceed with confidence. Second, these results must be field-checked. We suggest the use of a stratified random sampling scheme to do this. In addition, some obvious gaps in the ability to model the image arose from some conspicuous missing endmembers. In the future, improved models might result from a larger and more complete spectral library for this region.

Finally, an improved method must be found for choosing between three- and four-endmember models in arid and semi-arid environments. It is proposed that this method might take advantage of the large spectral changes in plants during their different phenological stages. Since grasses will show much more variation in greening and senescence than shrubs and also green at different times than shrubs, seasonal differences may give additional information to differentiate between these vegetation types. The ability to determine whether a three-endmember model or a four-endmember model is more appropriate for a given pixel is a crucial step that must included in the definition of a robust methodology for modeling arid environments using MESMA.

6. REFERENCES

Buffington, L.C., and Herbel, C.H., 1965, "Vegetational changes on a semidesert grassland range from 1858 to 1963", Ecological Monographs, v. 35, p. 139-164.

Duncan, J., Stow, D., Franklin, J., and Hope, A., 1993, "Assessing the relationship between spectral vegetation indices and shrub cover in the Jornada Basin, New Mexico", International Journal of Remote Sensing, v. 14, p. 3395-3416.

Ehleringer, J., 1981, "Leaf absorptances of Mohave and Sonoran Desert plants", Oecologia, v. 49, p. 366-370.

Escafadel, R., and Huete, A., 1991, "Improvement in remote sensing of low vegetation cover in arid regions by correcting vegetation indices for soil "noise"", C. R. Academie des Sciences Paris, v. 312, p. 1385-1391.

Franklin, J., Duncan, J., and Turner, D.L., 1993, "Reflectance of vegetation and soil in Chihuahuan desert plant communities from ground radiometry using SPOT wavebands", Remote Sensing of the Environment, v. 46, p. 291-304.

Gardner, M., 1997, Mapping Chaparral with AVIRIS Using Advanced Remote Sensing Techniques, Master of Arts thesis: Department of Geography, University of California, Santa Barbara, CA.

Green, R.O., Conel, J.E., and Roberts, D.A., 1993, "Estimation of aerosol optical depth and additional atmospheric parameters for the calculation of apparent surface reflectance from radiance measured by the Airborne Visible/Infrared Imaging Spectrometer", *in* Green, R.O., ed., Fourth Annual JPL Airborne Geoscience Workshop, Volume 1: Pasadena, CA, Jet Propulsion Laboratory, p. 73-76.

Green, R.O., Roberts, D.A., and Conel, J.E., 1996, "Characterization and compensation of the atmosphere for the inversion of AVIRIS calibrated radiance to apparent surface reflectance", *in* Green, R.O., ed., Sixth Annual JPL Airborne Earth Science Workshop, Volume 1: Pasadena, CA, Jet Propulsion Laboratory, p. 135-146.

Huete, A.R., Jackson, R.D., and Post, D.F., 1985, "Spectral response of a plant canopy with different soil backgrounds", Remote Sensing of Environment, v. 17, p. 37-53.

Huete, A.R., and Jackson, R.D., 1987, "Suitability of spectral indices for evaluating vegetation characteristics on arid rangelands", Remote Sensing of the Environment, v. 23, p. 213-232.

Huete, A.R., 1988, "A soil-adjusted vegetation index (SAVI)", Remote Sensing of Environment, v. 25, p. 295-309.

Huete, A.R., and Jackson, R.D., 1988, "Soil and atmosphere influences on the spectra of partial canopies", Remote Sensing of Environment, v. 25, p. 89-105.

Mabbutt, J.A., and Floret, C., 1980, "Case Studies on Desertification", United Kingdom, United Nations, Scientific and Cultural Organization.

Musick, H.B., 1984, "Assessment of Landsat Multispectral Scanner spectral indices for monitoring arid rangeland", IEEE Transactions on Geoscience and Remote Sensing, v. GE-22, p. 512-519.

Painter, T.H., Roberts, D.A., Green, R.O., and Dozier, J., 1997, "Improving mixture analysis estimates of snow covered areas from AVIRIS data", Remote Sensing of Environment, *in press*.

Paulsen, H.A., Jr., and Ares, F.N., 1962, "Grazing values and management of black gramma and tobosa grasslands and associated shrub ranges of the Southwest", Technical Bulletin 1270, U.S. Forest Service.

Pickup, G., Chewings, V.H., and Nelson, D.J., 1993, "Estimating changes in vegetation cover over time in arid rangelands using Landsat MSS data", Remote Sensing of Environment, v. 43, p. 243-263.

Ray, T.W., 1995, Remote Monitoring of Land Degradation in Arid/Semiarid Regions, Ph.D. thesis: Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA.

Ray T.W., and Murray, B.C., 1996, "Nonlinear spectral mixing in desert vegetation", Remote Sensing of Environment, v. 55, p. 59-64.

Roberts, D.A., Smith, M.O., and Adams, J.B., 1993, "Green vegetation, nonphotosynthetic vegetation, and soils in AVIRIS data", Remote Sensing of the Environment, v. 44, p. 255-269.

Roberts, D.A., Green, R.O., and Adams, J.B., 1997a, "Temporal and spatial patterns in vegetation and atmospheric properties from AVIRIS", Remote Sensing of Environment, v. 62, p. 223-240.

Roberts, D.A., Gardner, M.E., Church, R., Ustin, S.L., Scheer, G., and Green, R.O., 1997b, "Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models", Remote Sensing of Environment, *in press*.

Smith, M.O., Ustin, S.L., Adams, J.B., and Gillespie, A.R., 1990, "Vegetation in deserts: I. a regional measure of abundance from multispectral images", Remote Sensing of Environment, v. 31, p. 1-26.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., and Whitford, W.G., 1990, "Biological Feedbacks in Global Desertification", Science, v. 247, p. 1043-1048.

Sears, P.B., 1935, Deserts on the March: Norman, Oklahoma, University of Oklahoma Press.

Soil Conservation Service, 1980, "Soil survey of Dona Ana County area, New Mexico", United States Department

of Agriculture.
Warren, P.L., and Hutchinson, C.F., 1984, "Indicators of rangeland change and their potential for remote sensing", Journal of Arid Environments, v. 7, p. 107-126.