EVALUATING CHANGE IN RANGELAND CONDITION USING MULTITEMPORAL AVHRR DATA AND GEOGRAPHIC INFORMATION SYSTEM ANALYSIS

TIMOTHY B. MINOR[1*], JUDITH LANCASTER[1], TIMOTHY G. WADE[1], JAMES D. WICKHAM[2], WALTER WHITFORD[3] and K. BRUCE JONES[3]
[1] *Biological Sciences Center, Desert Research Institute, 7010 Dandini Blvd. Reno, Nevada 89512, U.S.A.;* [2] *Environmental Systems Division (MD-56), National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711, U.S.A.;*
[3] *Characterization Research Division/Office of Research and Development, National Exposure Research Laboratory, U.S. Environmental Protection Agency, Las Vegas, Nevada 89193, U.S.A.*
(author for correspondence, e-mail: tminor@dri.edu)*

(Received 6 June 1997; accepted 4 September 1998)

Abstract. Coarse-scale, multitemporal satellite image data were evaluated as a tool for detecting variation in vegetation productivity, as a potential indicator of change in rangeland condition in the western U.S. The conterminous U.S. Advanced Very High Resolution Radiometer (AVHRR) biweekly composite data set was employed using the six-year time series 1989–1994. Normalized Difference Vegetation Index (NDVI) image bands for the state of New Mexico were imported into a Geographic Information System (GIS) for analysis with other spatial data sets. Averaged NDVI was calculated for each year, and a series of regression analyses were performed using one year as the baseline. Residuals from the regression line indicated 14 significant areas of NDVI change: two with lower NDVI, and 11 with higher NDVI. Rangeland management changes, cross-country military training activities, and increases in irrigated cropland were among the identified causes of change.

Keywords: GIS, multitemporal analysis, NDVI, rangeland condition, remote sensing

1. Introduction

Time series analysis of coarse scale remote sensing data permits the measurement and analysis of change in rangeland condition at regional scales. Previous studies have shown that analyses of relationship between the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) visible and near-infrared-band satellite data from the NOAA series of polar orbiting meteorological satellites and terrestrial vegetation phenomena such as phenology and primary production were successful (Gray and McCrary 1981; Townshend and Tucker 1981; Tucker *et al*. 1984; Justice *et al*., 1985; Goward *et al*., 1985, 1991, 1993). The results of these studies encourage the use of AVHRR image data as a regional vegetation monitoring and assessment tool.

In this study, we utilize AVHRR spectral vegetation index measurements to evaluate the variability in rangeland condition in the state of New Mexico over the

Environmental Monitoring and Assessment **59:** 211–223, 1999.

time period 1989 to 1994. Specifically, we use the Normalized Difference Vegetation Index (NDVI) image band, derived from the conterminous U.S. AVHRR data set CD-ROM product developed by the Earth Resources Observation Systems (EROS) Data Center (EDC), an agency of the United States Geological Survey.

NDVI is the ratio of near-infrared and visible wavebands (Deering *et al.*, 1975), as defined in the following equation:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{VIS})/(\mathrm{NIR} + \mathrm{VIS}) \quad (1)$$

where Channel 2 (0.72–1.10 μm) of the instrument is used for the near-infrared (NIR) waveband and channel 1, the red band (0.58–0.68 μm), is used for the visible (VIS) waveband. NDVI measurements minimize the effects of topography and atmosphere (Holben and Justice, 1981), require no prior knowledge of ground conditions, and are sensitive to the amount of photosynthetically active vegetation present (Myneni *et al.*, 1992; Tucker, 1979). Computationally, NDVI measures the deviation of a vegetated pixel relative to a soil baseline (Huete and Tucker, 1991). Although secondary soil spectral effects do affect NDVI measurements over arid and semi-arid regions like New Mexico, NDVI can be implemented in large spatial scale studies.

To effectively assess changes in rangeland conditions in New Mexico, deviations in productivity as measured by NDVI were integrated with other spatial data such as precipitation, vegetation, and land ownership in a Geographic Information System (GIS) to determine the probable causes of change. Rangeland condition based on NDVI should vary with climate, and in rangelands the most important climatic variable driving productivity is generally precipitation. Anthropogenic disturbance can affect productivity both as a positive driver as well as negative, but should change the values of recorded NDVI relative to expected values based on precipitation. Anthropogenic activities that can drive NDVI in a positive direction include irrigation, fertilization, and changes in rangeland management practices, while soil disturbance and dramatic land use changes should move NDVI in a negative direction. In this study we hypothesize that anthropogenic variation in NDVI can be readily differentiated from natural variation especially when comparing regional scale NDVI pixel values over a time domain of several years. If such variations can be detected using coarse scale AVHRR imagery and assessed from records of land use, these data then have potential as an assessment and monitoring tool.

2. Study Area

The study involved a regional assessment of the state of New Mexico. The geographic extent of New Mexico includes portions of the Rocky Mountains, Rocky Mountain Piedmont, Colorado Plateau, and the Chihuahuan desert (Dick-Peddie, 1993). New Mexico consists of many microclimates due to its geographic extent and topographic variability. Temperature variations are caused more by elevation than geographic latitude within the state. Average annual precipitation is 380 mm, but like temperature, ranges dramatically with elevation. A high of 1000 mm has been measured in the upper parts of the Jemez and Sangre de Cristo mountains, whereas only 200 mm annually is observed in the San Juan and Chaco river basins. Vegetation cover varies widely over the state, from coniferous forest and mixed woodland in the northern part of New Mexico to dominant desertscrub/grassland communities in the south (Warren and Hutchinson, 1984). The major types of New Mexico vegetation are tundra, forest, woodland, grassland, scrubland, and riparian (Dick-Peddie, 1993). Extensive areas in the state are transitional or ecotonal areas, i.e., mixes between the major types.

3. Description of Data Sets

Conterminous U.S. AVHRR data sets for a six-year time series 1989 through 1994 were acquired from EDC. The conterminous U.S. AVHRR data sets contain a NDVI image band derived from a compositing technique using NOAA-11 satellite data. The AVHRR instrument has an Instantaneous Field of View (IFOV) of 1.3 mrad, with an overall field of view 55.4 degrees on either side of nadir. This geometry yields a nominal ground resolution of 1.1 km at nadir (NOAA, 1986). In 1990, EDC began the collection of daily AVHRR imagery as a part of a program to develop a series of calibrated, georegistered biweekly composite images of the conterminous United States (EDC, 1994; Eidenshink, 1992). The purpose of the compositing effort was to create a single, cloud-free image. Daily images collected over a 14 day period were combined into a single composite. Pixels for the composite were selected based on the highest daily NDVI value within the 14 day period. The NDVI equation produces results which are scaled between –1 and +1. These values were linearly rescaled into a 0–200 range, where –1 equals 0 and 1 equals 200. The underlying assumption is that values less than 100 in the NDVI image band represent clouds, snow or water while vegetated surfaces have values greater than 100 (Eidenshink, 1992).

The composite data sets have been radiometrically calibrated and corrected for variations in solar illumination (Eidenshink, 1992). The daily AVHRR images were georeferenced by rectifying them to a base image composed of approximately 20 near nadir cloud-free segments of NOAA-11 Channel 2 daily observations. These images were rectified to the USGS 1:2 000 000 hydrographic Digital Line Graph (DLG) data. Subsequent accuracy assessment verified a geometric root-mean-square error (RMS) of less than 1 pixel (EDC, 1994).

For the 1989–1994 data sets, an average of 17 biweekly observations covered the growing season (March-October) for each year, except 1994, which had only 14 observations due to the failure of the NOAA-11 satellite. A digital boundary of

TABLE I

Ancillary spatial data sets for New Mexico used in the study, and sources

Data set	Source
Hydrography	USGS 1:2 000 000 DLG
Land ownership	Earth Data Analysis Center
Meteorological stations	Western Regional Climate Center Desert Research Institute
Roads	USGS 1:2 000 000 DLG
Soils	USDA NRCS STATSGO Database
Topography	USGS 3 arc second DEM

TABLE II

New Mexico vegetation types and extent (from Dick-Peddie, 1993)

Vegetation type area in hectares	
Plains-mesa grassland	6 947 618
Desert grassland	5 458 915
Chihuahuan desert scrub	1 838 882
Great basin desert scrub	1 288 254
Plains-mesa sand scrub	1 667 489
Closed basin scrub	775 869

New Mexico was used to clip out a subset of the conterminous U.S. data for the state, and average NDVI was calculated for each pixel based on available dates, for each year of the time series.

In order to assess the relationship between NDVI change and rangeland condition in New Mexico, the satellite-derived NDVI values were integrated with other spatial data sets using a GIS system capable of integrating both raster and vector data. Arc/Info and ArcView (ESRI, 1996) were used in this study to integrate vegetation cover, land ownership, topography, hydrology, and meteorological station locations with the NDVI data. These data and sources are listed in Table I.

The vegetation cover data layer of the state was compiled by Dick-Peddie (1993). The data layer was modified to include only those vegetation types comprising rangeland cover. Using a simple spatial masking technique, upland vegetation, urban development, and agricultural areas were removed from the data layer, leaving the six vegetation types described in Table II.

4. Approach

Regression analyses were performed to identify areas of change in average NDVI, using values from the 1989 composite data as the independent variable and, successively, average NDVI values from each of the following years as the dependent variable. Once regression coefficients were calculated, areas of change were identified as outlier patches of pixels (residuals) which fell above and below the calculated regression line for at least four of the five years between 1990 and 1994. Using an iterative technique, deviations of 1.25 to 3 were calculated for each regression equation to evaluate the relationship between deviations and changes in the pattern and extent of outlier patches. In general, increasing the deviation did not create new outlier patches but instead altered the shape and extent of areas already identified using a smaller deviation. A deviation of two was eventually selected for analyses because it provided a reasonable number of pixels of both increased and decreased NDVI outliers.

To determine the relationship between precipitation and NDVI, outlier patches of increased or decreased NDVI were overlaid with meteorological station locations using the GIS system. A total of 182 stations distributed throughout the state were utilized. A 10.5 km square area of influence around each meteorological station was defined spatially using climate pattern and precipitation pattern data gathered by the Western Regional Climate Center (Redmond, 1995, personal communication). The establishment of this buffer area resulted in 25 stations within or in close proximity to the 14 significant areas of NDVI change. Seasonal mean rainfall was derived for each of the 25 stations of interest. Total difference in precipitation from the 1989 baseline was calculated for each of the outlier areas. Analysis of variance was performed comparing areas of reduced and increased seasonal averaged NDVI. Two methods were implemented: one which treated each overlapping area as an observation, the second used each pixel of overlap.

To gain a better understanding of the change in NDVI indicated by the regression analyses results, as well as validate the results, another method, Principal Components Analysis (PCA), was employed to characterize surface change in land-cover. PCA multivariate techniques have proven to be effective when applied to both short and long time series data to identify surface change (Fung and LeDrew, 1987; Eastman and Fulk, 1993; Hirosawa *et al*., 1996). These investigators found that the first two transformed variables in the PCA, i.e., Principal Components (PCs), represented the accumulated density and photosynthetic activity of vegetation during the period of analysis (1st PC) as well as the seasonal variability of vegetation (2nd PC). They also suggested that land-cover changes can be reflected in the minor components.

In this study we ran the PCA transformation on the six year time series, using each averaged NDVI image band as an input variable (six correlated variables). The resultant PCs image bands (six uncorrelated, transformed variables) were examined in a GIS framework relative to the regression results and several of the

TABLE III
ANOVA F ratio tests

Test 1	Test 2
Meteorological station buffer and outlier patch overlayed as a single observation	Each pixel of overlap as an observation
$F = 0.500$ (below critical value of 7.881) where $V1 = 2$; $V2 = 23$; $\alpha = 0.01$	$F = 2.195$ (below critical value of 6.7) where $V1 = 2$; $V2 = 396$; $\alpha = 0.01$

other ancillary spatial data sets, including vegetation cover and land ownership. In addition, the structure of the PCs' eigenvectors derived from the correlation matrix were analyzed.

5. Results

Using the regression analysis of the baseline and outyear average NDVI, 14 distinct patches with consistent change in four of the five years between 1990 and 1994 were identified. These patches were located in three main areas (Figure 1), with single pixels of change widely scattered throughout the state. Two of these areas reflected a reduction in NDVI relative to the 1989 baseline; a larger area located on the Fort Bliss military reservation, and the smaller near Farmington in the northwest corner of the state. These two areas accounted for 44 and 25%, respectively, of the total area of pixels with lower NDVI values.

Using the GIS system to perform a simple overlay comparison technique, these areas were evaluated relative to vegetation cover and land ownership. The two areas occurred in mixed communities of Desert Grassland/Chihuahuan Desert Scrub and Desert Grassland/Great Basin Desert Scrub. Remaining areas with lower NDVI between 1989 and 1994 were found on private land south of Albuquerque in Plains-Mesa Sand Scrub/Desert Grassland and on public land in Desert Grassland and Chihuahuan Desert Scrub. These remaining areas were mostly single pixels or small clusters of two to three pixels and may not reflect true change in NDVI. Areas with increased NDVI between 1990 and 1994 were found in large patches in northeast New Mexico (83%), mostly on private land in Plains-Mesa Grassland cover. Another significant patch of pixels with increased NDVI was identified on the Navajo Indian Reservation near the area indicating reduced NDVI described above. Other areas on state land were scattered and consisted of single pixels or small clusters in Chihuahuan Desert Scrub in the south and Closed Basin Scrub in the north.

Table III indicates the results of the ANOVA F ratio tests. Both methods resulted in F values well below critical values. The ANOVA tests confirmed that there were

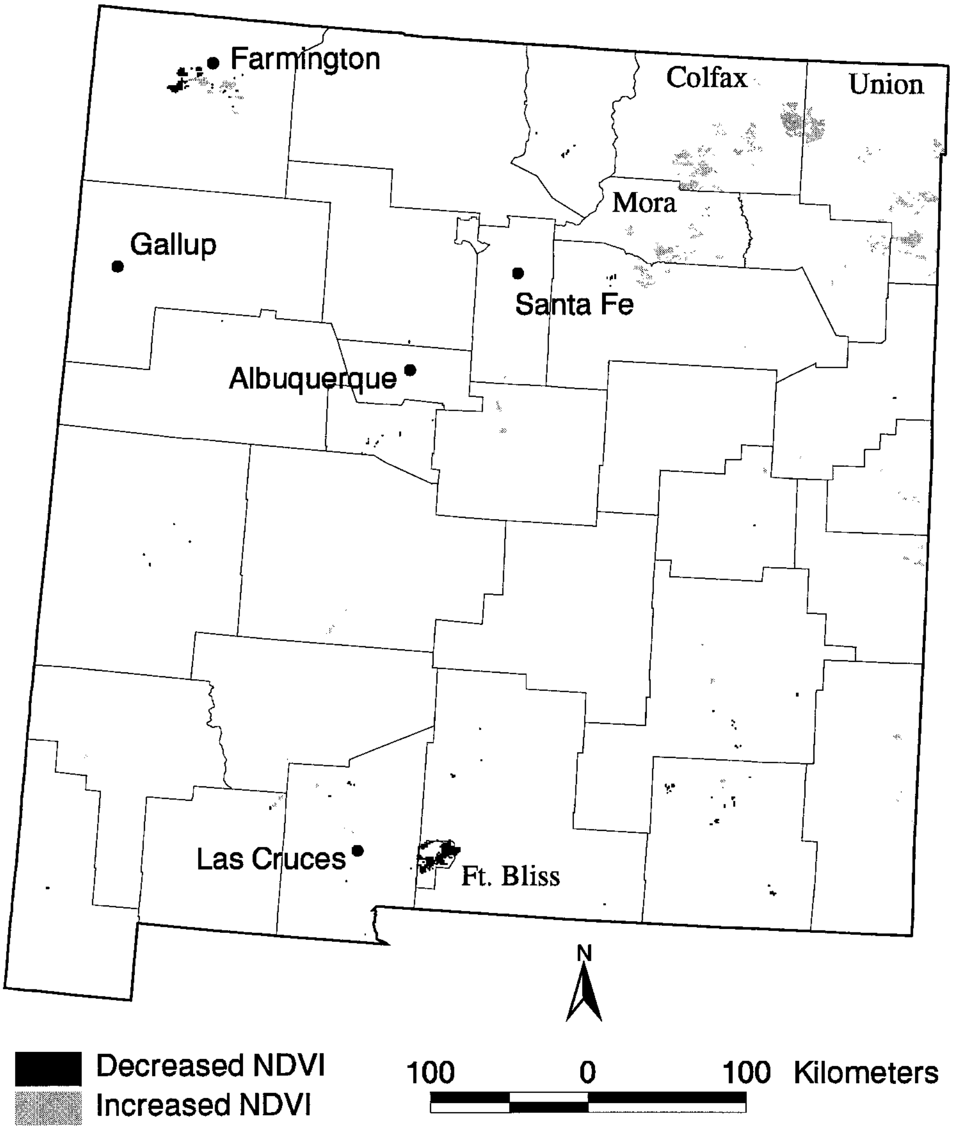

Figure 1. Areas in New Mexico with increased (gray) or decreased (black) average NDVI for the period 1989 to 1994.

no statistically significant difference between seasonal mean precipitation recorded at meteorological stations associated with either the increased or decreased NDVI outliers.

The Principal Components analyses indicated that the eigenvectors for PC1 were higher in value, positive, and very consistent over the six years of averaged NDVI in PC1. An analysis of the PC1 results relative to the other data sets in the GIS database revealed the spatial variation of the magnitude of NDVI (based on

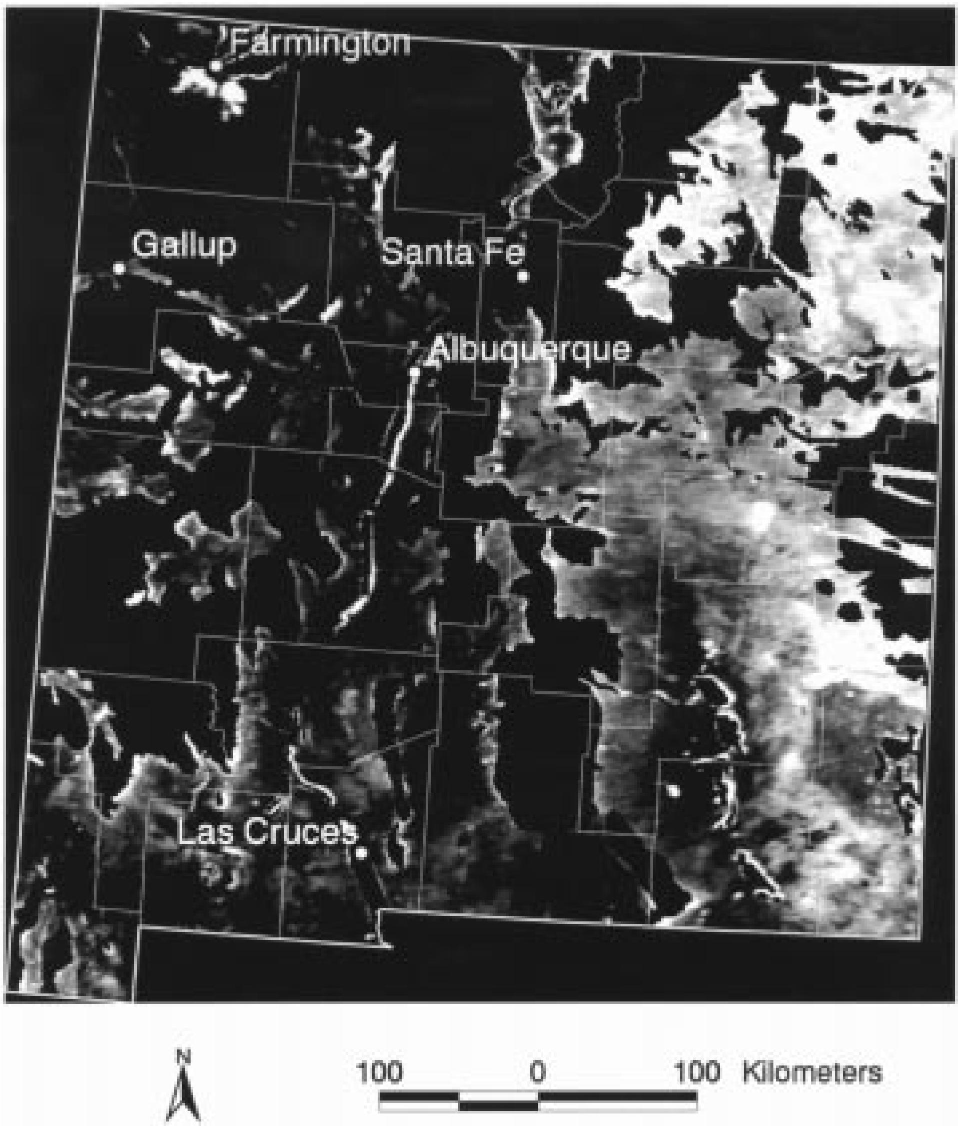

Figure 2. PC1 of average NDVI for New Mexico. Bright pixels indicate areas of increased NDVI and differences in vegetation phenology and density. Black regions are masked upland vegetation and agricultural areas.

the dissimilar vegetation communities and their differences in phenology and density), specifically the delineation of Plains Mesa grassland and Plains Mesa Sand Scrub communities (Figure 2). When compared to the regression outliers, the PC1 image highlighted (bright pixels) several of the increased NDVI outlier clusters, primarily in northeast New Mexico, but also south and west of Farmington in the northwest corner of the state (Figure 2). A small area of increased NDVI southeast of Albuquerque was also closely associated with bright PC1 pixels. It should be noted that in addition to identifying the areas of increased NDVI near Farmington, the PC1 image also highlighted several of the decreased NDVI outlier clusters in the same area. These anomalies could be a result of the eigenvector loadings in the first PC component, which can reflect absolute change in surface cover over time rather than specific increases or decreases in year to year NDVI response.

An evaluation of the PC2 eigenvectors revealed greater variation in the loadings as well as occurrence of both positive and negative eigenvectors, with a strong, negative loading for 1989 and a weaker, negative loading for 1992. PC2 obviously did not represent the seasonal pattern of vegetation change since that had been averaged out for each year; however, an analysis of the PC2 band relative to the regression results did indicate a close spatial correlation between the decreased NDVI outliers west of Farmington and those found within Fort Bliss (Figure 3). This indicates that PC2 reflects those components of the multitemporal data set that contain information on the decreased NDVI areas.

6. Discussion and Conclusions

Ten of the eleven areas with increased NDVI over the time series 1989 to 1994 occurred in four contagious clusters in Union, Colfax, and Mora Counties in the northeast corner of the state (Figure 1). Land is privately owned, and inquiries with County agents and the Bureau of Land Management (BLM) (McCormack, 1996, personal communication) indicated that there had been no increase in irrigated agriculture, no significant fires, and no new planting activities. However, there had been changes in livestock management practices in the early 1990s, including variations in grazing intensity, season, and pasture size which resulted in a transition from short grass to long grass species in the area. These variations were a result of a holistic resource management program employed in the region focusing primarily on time controlled grazing.

The eleventh area of increased NDVI occurred south and west of Farmington in the northwest corner of the state and is in close proximity to two areas of decreased NDVI (Figure 1). The increased NDVI area is located within the Navajo Indian Irrigation Project, where the areal extent of crop production increased significantly from 1990 to 1995 (24 000 to 32 000 ha). In addition, productivity increased in the area during this time due to changes in canopy density related to crop rotation (Buchanan, 1996, personal communication). The two decreased areas next to the Navaho Indian Irrigation Project are associated with the Four Corners Power Plant southwest of Farmington. The strip mines themselves are too small to be resolved with 1 km pixels. What may be reflected in the anomalous pixel clusters are the effects of a reclamation project around the mines in which reclaimed areas and reshaped spoils were regraded with top soil. These activities, however, should have provided the opposite effect, i.e. increased NDVI, over the time series since with

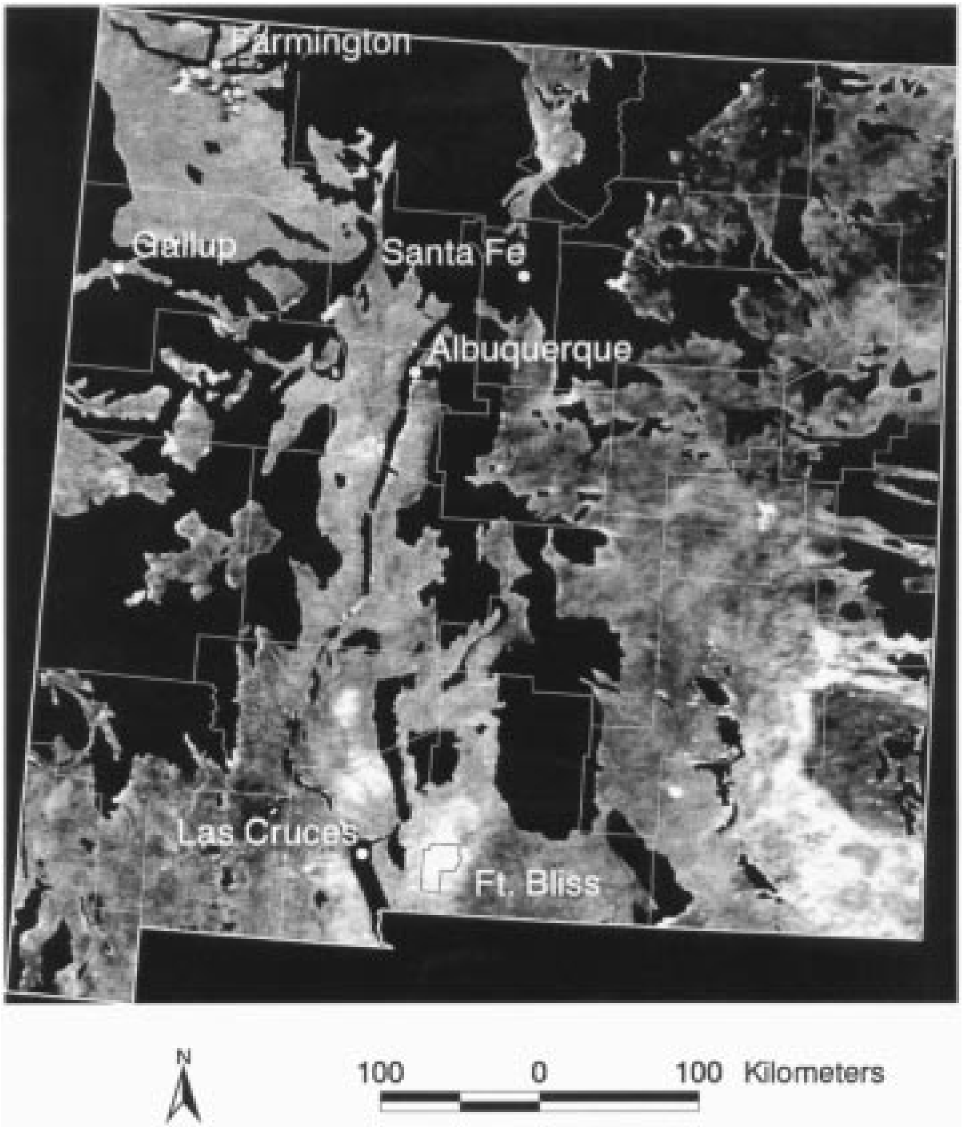

Figure 3. PC2 of average NDVI for New Mexico. Bright pixels indicate areas of decreased NDVI and differences in vegetation phenology and density. Black regions are masked upland vegetation and agricultural areas.

the application of top soil, subsequent seeding and irrigation would have caused a green-up during the early 1990s.

A combination of natural and anthropogenic activity may have contributed to the largest of the areas indicating decreased NDVI located on the Fort Bliss Military Reservation in the southern part of the state (Figure 1). Combining the NDVI results with land ownership information in the GIS, the decreased NDVI pixels were found almost exclusively within the Fort Bliss reservation boundary. Personnel with Ft. Bliss' Directorate of Environment have indicated that the areas defined by the pixel clusters were used consistently for tank maneuvers from 1972 to 1995 (Bush, 1996, personal communication). Although this may not totally explain the changes in NDVI signal observed from 1989 to 1994, it implies that the potential for degradation in these areas is high, given the activity involved and the sparse mesquite composite cover and annual grasses found in the area. Further analysis of vegetation patterns, geomorphology, and precipitation patterns on this part of the military reservation will be necessary to pinpoint the exact reason for the anomalous pixel clusters, but in all likelihood, the cause is a cumulative effect prompted by the cross-country training activities.

The ANOVA results established that the areas of changed NDVI identified by regression analysis were not directly caused by precipitation variability, but rather by changes in productivity and/or biomass. These results, however, may be partially biased by sampling differences between measured NDVI and the precipitation data (cell-based data [AVHRR] vs. discrete point data [meteorological stations]). A comparison between measured NDVI and an interpolated surface of precipitation data may have been more accurate but was beyond the scope of this paper.

The PCA analysis results, in general, appear to verify the NDVI changes found using the regression techniques, but also express the spatial variation of the magnitude of NDVI related to phenology and density of vegetation. In addition, PC1 and PC2 do not exclusively map, respectively, increased and decreased NDVI pixels. PC1, in particular, mapped several areas of decreased NDVI. This could occur because the eigenvector loadings in PC1 reflect absolute change over time rather than increases or decreases in NDVI from year to year. The use of Principal Components Analysis in change detection requires a careful evaluation of the eigenstructures and images of the principal components.

This study has demonstrated that coarse scale satellite data may be effectively utilized to detect both increases and decreases in productivity in rangeland vegetation based on the relationship between averaged NDVI and net primary productivity or biomass. The use of a GIS system capable of integrating both raster and vector data greatly aided the analysis, both by permitting the spatial correlation between variables and by facilitating the evaluation of spatial parameters using statistical techniques. The methods described here are simple and straightforward, and could be used to make rapid assessments of change in rangeland condition at regional scales providing managers with baseline data for making rangeland management decisions.

Acknowledgements

This work was funded in part by the U.S. Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP) under Cooperative

Agreement CR-819549-0105 to the Desert Research Institute. This manuscript has not been reviewed by the Environmental Protection Agency and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. We acknowledge advice and information provided by William Dick-Peddie; Jeff Herrick, USDA Las Cruces; Doug Kliman, Stuart Marsh and Chuck Hutchinson, Office of Arid Lands Studies, University of Arizona, Tucson; Dorothy Miller and Kelly Redman, Western Regional Climate Center, Reno; Curtis Monger, New Mexico State University; and Kevin Von Finger, Brian Locke and Dallas Bush, Fort Bliss Military Reservation.

References

Deering, D. W., Rouse, J. W., Haas, R. H. and Schall, J. A.: 1975, Measuring forage production of grazing units from Landsat MSS data. *Proceedings of the 10th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, 1169–1179.

Dick-Peddie, W. A.: 1993, *New Mexico Vegetation: Past, Present, and Future*, University of New Mexico Press, Albuquerque.

EROS Data Center: 1994, Conterminous United States AVHRR data on CD ROM–Users Manual. U.S. Department of Interior, EROS Data Center, Sioux Falls, SD.

Eastman, R. J. and Fulk, M.: 1993, 'Long sequence time series evaluation using standardized principal components', *Photogrammetric Engineering and Remote Sensing* **59**(8), 1307–1312.

Eidenshink, J. C.: 1992, 'The 1990 Conterminous U.S. AVHRR Data Set', *Photogrammetric Engineering and Remote Sensing* **58**, 809–813.

ESRI: 1996, Arc/Info and ArcView, Environmental Systems Research Institute, Inc., Redlands, California.

Fung, T. and LeDrew, E.: 1987, 'Application of principal components analysis to change detection', *Photogrammetric Engineering and Remote Sensing* **53**(12), 1649–1658.

Goward, S. N., Dye, D. G. and Tucker, C. J.: 1985, 'North American vegetation patterns observed by NOAA-7 AVHRR', *Vegetatio* **64**, 3–14.

Goward, S. N., Markham, B., Dye, D. G., Dulaney, W. and Yang, J.: 1991, 'Normalized Difference Vegetation Index measurements from the AVHRR', *Remote Sensing of Environment* **35**, 257–277.

Goward, S. N., Waring, R. H., Dye, D. G. and Yang, J.: 1993, 'Ecological remote sensing at Otter: satellite macroscale observations', *Ecological Applications* **4**, 322–343.

Gray, T. I. and McCrary, D. C.: 1981, *Meteorological satellite data-A tool to describe the health of the World's agriculture*. AgRISTARS Report EW-NI-04042, JSC, Houston, Texas.

Hirosawa, Y., Marsh, S. E. and Kliman, D. H.: 1996, 'Application of standardized principal analysis to land-cover characterization using multitemporal AVHRR data', *Remote Sensing of Environment* **58**, 267–281.

Holben, B. N. and Justice, C. O.: 1981, 'An examination of spectral band ratioing to reduce the topographic effect on remotely sensed data', *International Journal of Remote Sensing* **2**, 115–121.

Huete, A. R. and Tucker, C. J.: 1991, 'Investigation of soil influences in AVHRR red and near-infrared vegetation index imagery', *International Journal of Remote Sensing* **12**, 1223–1242.

Justice, C. O., Townshend, J. R. G., Holben, B. N. and Tucker, C. J.: 1985, 'Analysis of the phenology of global vegetation using meteorological satellite data', *International Journal of Remote of Remote Sensing* **6**, 1271–1381.

Myneni, R. B., Ganapol, B. D. and Asrar, G.: 1992, 'Remote sensing of vegetation canopy photosynthetic and stomatal conductance efficiencies', *Remote Sensing of Environment* **42**, 217–238.

NOAA: 1986, NOAA polar orbiter user's guide. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data and Information Service, National Climate Data Center, Satellite Data Services Division, Washington, D.C.

Townshend, J. R. G. and Tucker, C. J.: 1981, Utility of AVHRR of NOAA 6 and 7 for Vegetation Monitoring. *Proceedings of Matching Remote Sensing Technologies and Their Applications* (Reading, England: Remote Sensing Society).

Tucker, C. J.: 1979, 'Red and photographic infrared linear combinations for monitoring vegetation', *Remote Sensing of Environment* **8**, 127–150.

Tucker, C. J., Vanpraet, C. L., Boerwinkle, E. and Easton, A.: 1984, 'Satellite remote sensing of total dry matter accumulation in the Senegalese Sahel', *Remote Sensing of Environment* **13**, 461–469.

Warren, P. L. and Hutchinson, C. F.: 1984, 'Indicators of rangeland change and their potential for remote sensing', *Journal of Arid Environments* **7**, 107–126.