APPLYING SATELLITE IMAGERY TO TRIAGE ASSESSMENT OF ECOSYSTEM HEALTH

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Abstract. Considerable evidence documents that certain changes in vegetation and soils result in irreversibly degraded rangeland ecosystems. We used Advanced Very High Resolution Radiometer (AVHRR) imagery to develop calibration patterns of change in the Normalized Difference Vegetation Index (NDVI) over the growing season for selected sites for which we had ground data and historical data characterizing these sites as irreversibly degraded. We used the NDVI curves for these training sites to classify and map the irreversibly degraded rangelands in southern New Mexico. We composited images into four year blocks: 1988–1991, 1989–1992, and 1990–1993. The overlap in pixels classified as irreversibly degraded ranged from 42.6% to 84.3% in year block comparisons. Quantitative data on vegetation composition and cover were collected at 13 sites within a small portion of the study area. Wide coverage reconnaissance of boundaries between vegetation types was also conducted for comparisons with year block maps. The year block 1988–1991 provided the most accurate delineation of degraded areas. The rangelands of southern New Mexico experienced above average precipitation from 1990–1993. The above average precipitation resulted in spatially variable productivity of ephemeral weedy plants on the training sites and degraded rangelands which resulted in much smaller areas classified as irreversibly degraded. We selected imagery for a single year, 1989, which was characterized by the absence of spring annual plant production in order to eliminate the confounding effect of reflectance from annual weeds. That image analysis classified more than 20% of the rangelands as irreversibly degraded because areas with shrub-grass mosaic were included in the degraded classification. The single year image included more than double the area classified as irreversibly degraded by the year blocks. AVHRR imagery can be used to make triage assessments of irreversibly degraded rangeland but such assessment requires understanding productivity patterns and variability across the landscapes of the region and careful selection of the years from which imagery is chosen.

Key words: AVHRR imagery, coppice dunes, desert rangelands, irreversible degraded, regional classification

1. Introduction

The need for relatively inexpensive and rapid means of assessing ecosystem health is widely recognized (Rapport 1992; Hunsaker and Carpenter, 1990). Making assessments and monitoring ecosystem health of large geographic regions on the basis of data collected on the ground poses a daunting sampling problem in addition to the prohibitive costs of such efforts. If much of the sampling can be done by

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analysis of satellite imagery, some of the cost and sampling problems may be tractable.

Because virtually all regions of North America, or indeed of the world, have experienced more than a century of industrial development, commercialization of agriculture and/or commercial timber, and mineral and biological resource exploitation, the health of the ecosystems of a region can vary from virtually dead to robustly healthy. For ecosystems at the least healthy end of the spectrum, restoration to a healthy state may be virtually impossible within the limitations of available technology. Therefore a triage assessment that can accurately identify the irreversibly degraded (virtually dead) ecosystems can provide information that is critical in assessing the health of ecosystems of a region and in designing monitoring programs for the future and/or designing land management and remediation plans.

In the human health analogy, triage assessments are based on a vast historical information base that provides the means of evaluating the probability of recovery of a patient given the resources available at the time. Ecosystem health triage assessments can be made on a similar basis. In this paper, we review the published information upon which a triage assessment of the health of Chihuahuan Desert rangeland can be made. We then use ground based data and satellite imagery to develop a reliable classification system for irreversibly degraded rangeland. Finally we test that system using 6 years of Advanced Very High Resolution Radiometer (AVHRR) imagery to determine if the irreversibly degraded areas boundaries coincide despite interannual climate variation. If interannual variation in climate had an effect on the boundaries of areas classified as irreversibly degraded, then we searched for classification rules that would provide an accurate assessment of the extent and location of irreversibly degraded areas.

1.1. IRREVERSIBLE DEGRADATION

In the northern Chihuahuan Desert, degradation of rangelands and the concomitant reduction in livestock production has been occurring at varying rates over the past one and one-half centuries (Buffington and Herbel, 1965; Hennessy *et al.*, 1983; Hastings and Turner, 1965). Reductions in livestock production have resulted from the reduction in cover or complete disappearance of grasses and replacement of grassland with shrubland (Gardner, 1951; Buffington and Herbel, 1965; Hennessy *et al.*, 1983). In the most extreme case, the species-rich grasslands are transformed into virtual monocultures of creosotebush (*Larrea tridentata*) shrubland or mesquite (*Prosopis glandulosa*) coppice dunes. These ecosystems are considered the most degraded because of the loss of topsoil or fine (silt) fraction and by the absence of suitable forage plants for livestock (Grover and Musick, 1990). When the ecosystems have degraded to a shrub-dominated system, exclusion of livestock has neither resulted in improvement in productivity nor change toward a grassland (Gibbens *et al.*, 1993 and unpublished records USDA-ARS Jornada Experimental Range). There have been numerous efforts to restore some level of productivity to these ecosystems by using herbicides to kill the shrubs, but these have been successful for only short time periods and are not economically feasible (Whitford, 1995; Herbel *et al.*, 1983; Gould, 1982). Even more aggressive efforts such as root-plowing the shrubs and re-seeding the furrowed landscape with a mixture of grasses or bulldozing the coppice dunes have provided only partial restoration of productivity, and the shrubs are increasing on these areas (Whitford, 1995).

As a consequence of this body of evidence, these shrub-dominated, unproductive ecosystems are judged to be irreversibly degraded. Indeed the dominant shrub species in these ecosystms are resistant to climate stress such as drought and are very resilient when subjected to repeated climatic stress (Whitford *et al.*, 1995). At present, efforts to restore, the irreversibly degraded rangelands have been abandoned and the focus has shifted to small-scale, low-energy input strategies that may result in small productive patches, and to alternate uses of the degraded ecosystems (other than livestock production). Thus the probability that monoculture creosote-bush ecosystems or mesquite coppice dune ecosystems will recover or be restored is virtually zero. Under triage, that probability consigns these ecosystems to the category of 'do not attempt to revive and no further monitoring required'.

Having identified the characteristics of the ecosystems that triage evaluation judges as requiring no further monitoring, land managers need to be able to identify and locate the irreversibly degraded patches within the landscapes for which they have responsibility. Satellite imagery has been used to generate land surface maps and general vegetation maps. Imagery from the NOAA satellite (AVHRR imagery) has been used to produce vegetation maps of desert rangeland (Peters *et al.*, 1993). Although that imagery was for a single year and none of the vegetation units were accuracy-assessed with ground data, the results demonstrated that AVHRR data could be used to map vegetation units in the semi-arid and arid conditions of New Mexico. If AVHRR imagery is to be used to make triage assessments of the ecosystems of a region, the locations and boundaries of the irreversibly degraded areas should remain constant over a series of years despite climate variability. If boundaries of irreversibly degraded areas do not remain constant over a series of years, we then need to identify characteristics of the imagery for years in which we were able to make the most accurate assessment. We hypothesized that the boundaries of irreversibly degraded systems would not vary temporally but that the boundaries of healthy or at-risk ecosystems would vary considerably. Here we report the results of a test of this hypothesis based on ground-calibrated imagery for rangelands in southern New Mexico.

2. Study region

We studied a portion of the northern Chihuahuan Desert rangeland in southern New Mexico (Figure 1). Precipitation is generally less than 300 mm per year and is highly variable. Monsoonal moisture, and associated summer thunderstorms,

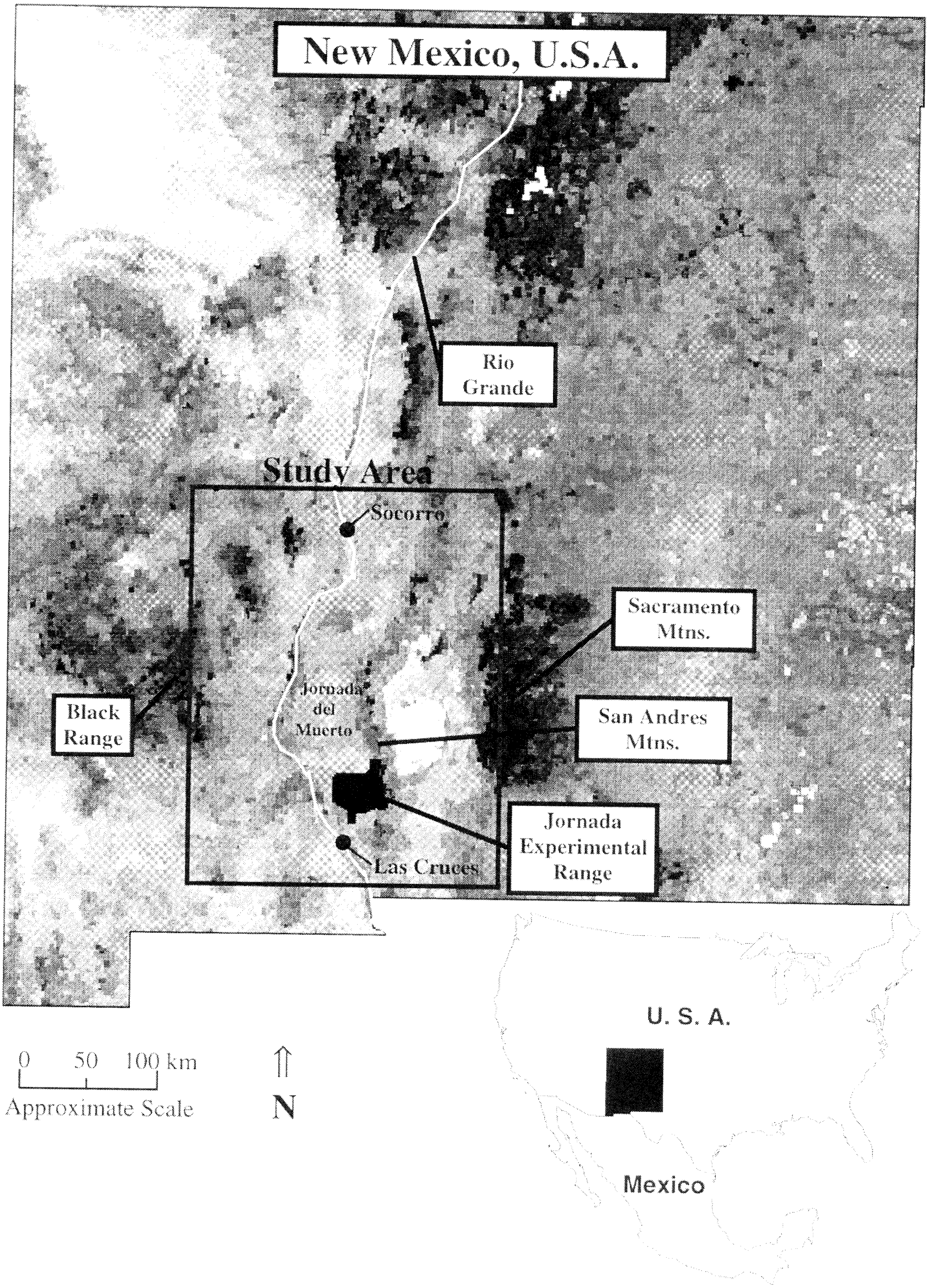

Figure 1. Location of the study area in the United States.

provide most of the rainfall, with 52% of the annual average falling in July, August and September.

The study area has commonly been referred to as desert grassland (Dick-Peddie, 1993). Prior to the development of the livestock industry in the mid 19th century, the rangeland lanscape was a mosaic of grassland with desert scrub occupying the hotter, drier sites (Gardner, 1951; Buffington and Herbel, 1965; York and Dick-Peddie, 1969; Dick-Peddie, 1975). Today the inverse is true, Chihuahuan Desert scrub dominates the landscape with grasslands limited primarily to more mesic sites (Dick-Peddie, 1975).

3. Methods

We obtained imagery from the National Oceanic and Atmospheric Administration's (NOAA) operational polar orbiting satellites' Advanced Very High Resolution Radiometer (AVHRR). The AVHRR system produces information in several different formats; we used High Resolution Picture Transmission (HRPT) data which are transmitted continuously in real time as the satellite passes overhead (NOAA, 1991).

Characteristics of the AVHRR system include coarse spatial resolution (1100 m at nadir), high temporal resolution (twice-daily coverage), high radiometric resolution (1024 gray levels), and a synoptic view (scanning ± 55 degrees from satellite orbital track). When compared to other earth-observation satellite data, AVHRR data are relatively inexpensive (less than $100 per scene). The coarse spatial resolution is suitable for regional studies. Also cloud-free data are more easily acquired with AVHRR because of the frequent coverage. This is especially important when using data acquired during rainy seasons.

Temporal imagery from the NOAA-AVHRR system was analyzed as a technique for triage of landscape health. This required the acquisition of satellite data, image processing to minimize radiometric and geometric error, and data analysis. Images were selected for 10–12 dates that were relatively evenly spaced through each growing season fom 1988 through 1993 (Table I). Selection was based on the following criteria:

1. Satellite nadir track within or very near the study area to minimize geometric and atmospheric distorion due to increasing scan angles.
2. Minimal cloud contamination and atmospheric attenuation.
3. Even spacing of dates throughout the growing season.

All data chosen were from the descending NOAA orbital track with a south-bound equatorial crossing at 7:30 am local standard time. Thus the satellite was recording data over the study area about 7:22 am standard time. The early morning overpass was chosen primarily because of the higher probability of clear sky conditions during the summer, since convective clouds commonly form by afternoon. This study utilized the spectral information recorded by Channel 1 (RED) (Visible

Table I

Dates for which AVHRR satellite data were used in the analyses. Dates followed by (a) had a few pixels with cloud contamination, dates followed by (b) had cloud contamination for sufficient pixels that the images were not used in the supervised classification. Images from dates followed by (b) were used in the generation of the temporal curves

1988	1989	1990	1991	1992	1993
Mar 21	Apr 04	Apr 14	Apr 29	Mar 14	Mar 24
Apr 12	Apr 18 (b)	May 06	May 12	Apr 07 (n)	Apr 26
Apr 26	May 02	May 20	May 29	Apr 21 (b)	Mar 10
Ma 15	May 19	Jun 02	Jun 15	Apr 29	Jun 02
Jun 07	Jun 07 (b)	Jun 23 (a)	Jun 24 (a)	Jun 02	Jun 12
Jun 21	Jun 20 (b)	Jul 07 (b)	Jul 06 (b)	Jun 11	Jul 05 (b)
Jul 13 (b)	Jul 04 (a)	Jul 28 (b)	Jul 28 (b)	Jul 05	Jul 24 (b)
Jul 22	Jul 22 (b)	Aug 24 (a)	Aug 27 (b)	Aug 02 (b)	Aug 11 (b)
Aug 14 (b)	Aug 09 (b)	Sep 11 (b)	Sep 08 (a)	Aug 21	Sep 03
Sep 07 (a)	Sep 04	Oct 11	Sep 24 (b)	Sep 09	Sep 18
Sep 25	Sep 18	–	Oct 04	Sep 28	Oct 21
Oct 08 (b)	Oct 10	–	Oct 18	Oct 12	–

red; 0.58–0.68 μm), Channel 2 (NIR) (near-infrared; 0.725–1.10 μm), and Channel 4 (TIR) (thermal-infrared; 10.50–11.50 μm). The dates of imagery used in this study are provided in Table I.

Prior to analysis, the satellite imagery was carefully calibrated. Each channel (RED, NIR and TIIR) was extracted from magnetic tape for a large area that included our study area. During downloading, the visible and near-infrared channels were converted from raw brightness values to refectance (Di and Rundquist, 1994).

Geometric Correction

Each data set was corrected for solar-angle variation using the solar zenith angle information appended during processing procedures at the Eros Data Center (NOAA, 1991; Di and Rundquist, 1994). This correction was not applied to the thermal channel because it is not reflected energy. Initial geometric adjustments were also made utilizing the locational coordinates embedded in the raw data. Plate Carree (equirectangular X/Y) coordinates were calculated for each pixel. This process places the image, which is locationally distorted by the satellite sensor scan angle, to a Plate grid, which is similar to a latitude/longitude coordinate system. Nearest-neighbor resampling was utilized in order to maintain the greatest accuracy of the original data. The remainder of the image processing was conducted on a personal computer using Earth Resources Data Analysis System (ERDAS; ERDAS, Inc., Atlanta, GA) image processing and GIS software.

Because of the temporal nature of this study, locational accuracy of each scene is critical. Errors, for instance, could mean that a pixel would appear as water on one date and vegetation on another. On-board clock synchronization of the TIROS satellite is subject to a plus or minus $\frac{1}{2}$ second error over a period of several months. Because the earth location information appended to the image is based on the satellite clock time, any clock error will be reflected as locational error (NOAA, 1991). In spite of this error, per-pixel relationships within any one scene remain accurate. This makes it possible to interactively adjust each image to obtain locational accuracy to within one pixel.

One scene was selected as a standard. Locational accuracy of the standard scene was accomplished by checking latitude/longitude locations of distinct points on the image (lava flows) with their corresponding map coordinates from 1 : 24 000 USGS topographic maps. Adjustment was made until image features were at the same location as the corresponding map features. Consequently, each additional scene was adjusted until distinct features lined up with the same features on the standard scene.

At the equator, degrees of latitude and longitude per pixel would be equal. But at the center of the study area this is not the case. Within the study area, each pixel was computed to represent 0.01177 degrees of longitude (X) and 0.00992 degrees of latitude (Y). A first-order transformation was utilized with nearest neighbor resampling to correct for pixel size.

Atmospheric Calibration

Each date of imagery was independetly reviewed for cloud contamination. By utilizing the visible and thermal differences between cloud and land surfaces, clouds and cloud shadow areas were interactively identified. This information was used to create a mask separating cloud and cloud shadow contaminated areas from non-contaminated areas. An independent cloud mask was generated for each data of imagery exhibiting cloud contamination. The mask was used to convert contaminated pixels to a value of 'O,' thus elimating clouds and cloud shadows from each date of imagery.

Of the 69 images acquired for this study, 42 were completely cloud free over the study area. An additional six scenes had minimal cloud contamination that was not over the desert basins. The cloud masks for these six images were merged into one and used to mask these cloud areas from the entire image set. The remaining 21 images had cloud contamination that was sufficiently extensive that they were elimated from the supervised classification reported here. However, these dates were cloud masked and the cloud-free portions provided valuable information on the temporal dynamics of NDVI (Figure 2) ((Peters *et al.*, 1997).

As solar radiation interacts with the earth's atmosphere, some selective scattering and adsorption occur introducing distortion into terrain measurements (Jensen, 1996). For the purposes of this study, an atmospheric standardization step was implemented. The technique developed is a modification of what Jensen (1996) calls histogram adjustment. Clear deep water absorbs nearly all of the incoming solar energy, especially in the infrared portion of the spectrum. We standardized

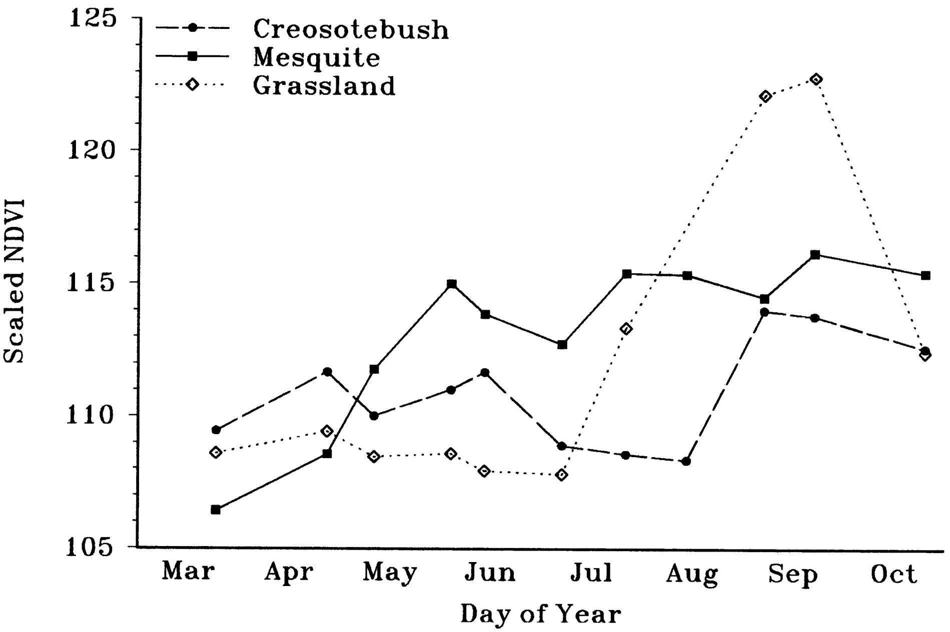

Figure 2. Characteristic NDVI growing season curves for creosotebush (*Larrea tridentata*) dominated shrublands and mesquite (*Prosopis glandulosa*) coppice dune areas. The NDVI curve of a C_4 grassland is included for comparison.

scene brightness values across all dates of imagery based on brightness over a deep water portion of Elephant Butte Reservoir. While this technique does not completely eliminate atmospheric attentuation, it will standardize the atmospheric component across all dates of imagery without introducing zeros or potentially negative numbers into the data sets.

Vegetation Index Computation

The RED and NIR data were then used to compute NDVI for each date of imagery. Unscaled NDVI produces a value between –1.0 and +1.0. Because growing vegetation strongly reflects NIR energy and absorbs RED energy, positive values should be indicative of actively photosynthesizing vegetation, while values less than or equal to zero represent water, bare soil, or other non-vegetated surfaces (Gutman, 1991; Lillesand and Kiefer, 1994; Peters *et al.*, 1997). Multiplying by 100 results in an index value that maintains its original index identity and allows this value to be stored in an 8-bit format for future display and analysis. Since a large component of each pixel could be bare soil, it was determined that negative NDVI values may provide additional useful information. The NDVI computation used for this research was:

$$NDVI = ((NIR\text{-}RED)/(NIR + RED) + 1.0) * 100$$

where *NDVI* is the normalized difference vegetation index, *NIR* is the AVHRR band 2 reflectance, and *RED* is the AVHRR band 1 reflectance. This computation resulted in a value of 100 for an NDVI of 0.00 with negative NDVI values being less than 100 and positive greater than 100. NDVI images for each year were composited in chronological order resulting in one temporal NDVI file for each year with the first date of NDVI as band 1, the second as band 2, and so on.

The final step was to eliminate non-desert areas from each data file. To accomplish this, an unsupervised iterative classifier (ISODATA; ERDAS, 1991) was implemented on the cloud-free dates of 1989 NDVI imagery. The year 1989 was selected because the desert basins suffered a winter–spring drought, enhancing the temporal/spectral separability of desert and non-desert areas (Peters and Eve, 1995). An interactive approach for recombining the ten temporally distinct signatures resulting from the classification was implemented. Signature similarities and the spatial pattern of each temporal class in the classified image were evaluated. The result was temporal NDVI curves for the general vegetation types (Figure 2). Field data and existing vegetation maps were also utilized. Further post-classification merging resulted in two classes: one representing desert and the second representing non-desert areas. The non-desert areas included forests, woodlands, riparian and agricultural lands (Figure 3). The desert areas included desert shrublands, arid and semi-arid grasslands, and barren areas such as White Sands National Monument. This information was used to eliminate all of the non-desert areas from each of the image dates. The remainder of the analysis was conducted on only the desert portions of the study area.

Supervised classification

To provide a triage assessment of landscape health based on AVHRR imagery, we had to identify landscape units of sufficient size (> 3 km on a side) that fit the description of irreversibly degraded. Because of the long history of restoration research and the well documented record of historical vegetation change (Buffington and Herbel, 1965), we chose sites on the Jornada Experimental Range. Additional severely degraded sites in southern New Mexico were chosen on the basis of their structural similarity to the Jornada sites. Since this analysis was focused on delineating the irreversibly degraded portions of the study area, a variety of sites were selected that represented most of the variability in severely degraded Chihuahuan Desert landscapes. In addition, less degraded sites were identified but that analysis is not presented here. These irreversibly degraded areas were then utilized as training sites in a supervised classification of the multi-date AVHRR-NDVI imagery. This delineated all of the regions of the study area that had NDVI temporal signatures similar to the training sites. If the use of NDVI temporal signatures successfully delineate severely degraded areas, such areas should consistently classify as being temporally similar to the training sites.

We selected six training sites (3 in mesquite coppice dunes and 3 in creosotebush-gravelly pavement areas). Each site was between 16 and 20 AVHRR pixels in size

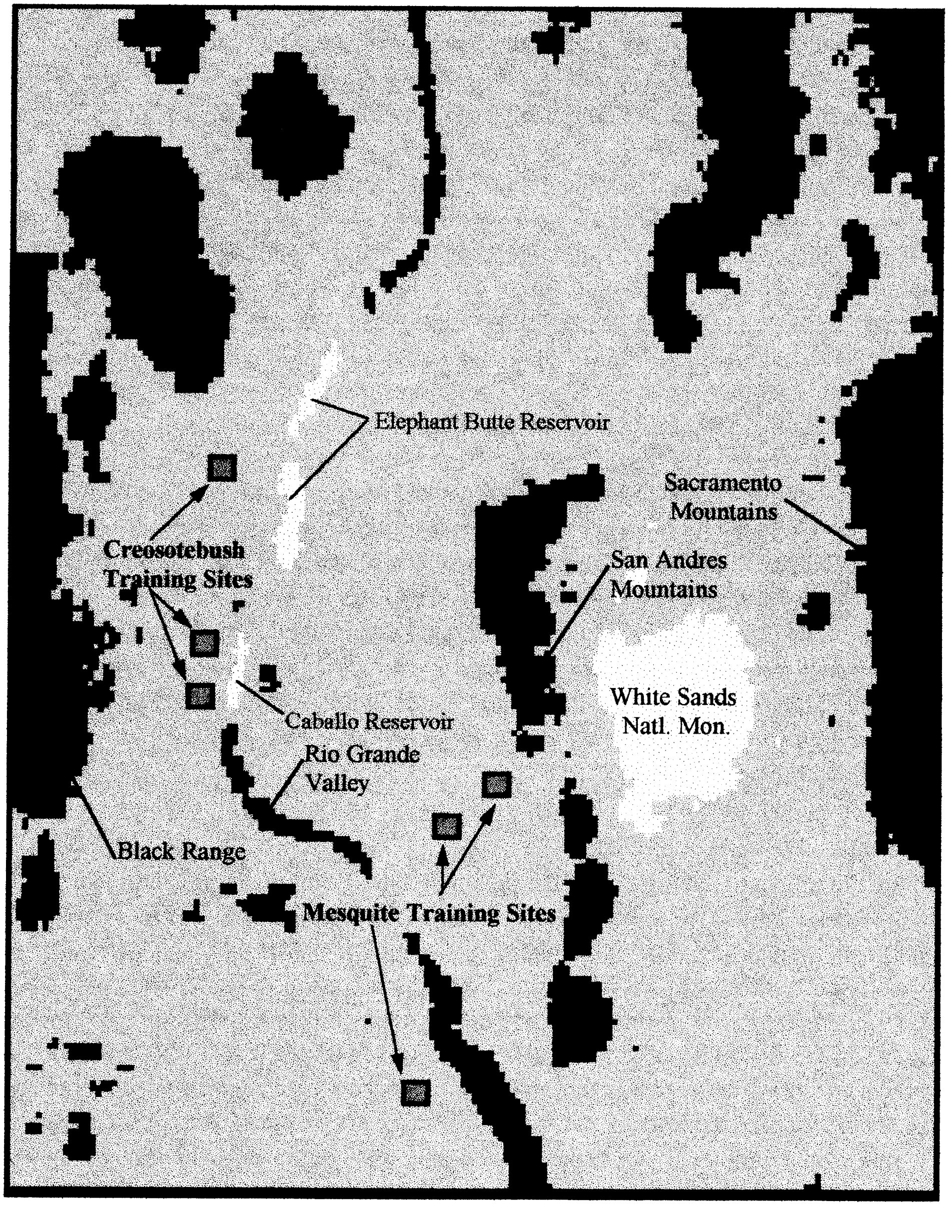

Figure 3. Delineation of the desert grassland and shrubland rangelands of southern New Mexico with the non-rangeland areas masked.

(approximately 20–25 km^2). The mesquite coppice dune sites were on sandy-loam soils. The vegetative cover ranged from 0.0–1.6% grass and from 26% to 36% shrub cover primarily of mesquite, *Prosopis glandulosa*. The mesquite forms a coppice of short stems on the tops of sand dunes. The bare patches between the vegetated dunes average 30 to 40 m in diameter. The creosotebush-gravelly pavement sites were in piedmont slopes with gravelly surfaces. Creosotebush, *Larrea tridentata*, canopies provided between 20% and 23% cover. The creosotebush training sites had little to no grass cover.

A supervised classification was conducted on cloud-free dates of AVHRR-NDVI for each of the six growing seasons (1988 through 1993). The training statistics for each year's classification were generated from the temporal NDVI values for that year and each site was maintained as a distinct signature. Following classification, the six output classes (resulting from the six training sites) were ultimately merged into a single class identified as 'severely degraded.' The supervised classification utilized was MAXCLAS within the ERDAS image processing and GIS software. Within MAXCLAS we used the maximum likelihood decision rule after an optimization using a parellelepiped decision rule (ERDAS, 1991). This classifer allow landscape areas that are not statistically similar to the training sites (which represent only the most severely degraded condition) to remain unclassified. Independent supervised classification of temporal NDVI data sets for each year resulted in six images, each identifying areas that had the appearance of the severely degraded training sites during that growing season.

Precipitation variability and fluxes in nutrient availability can result in highly variable biomass production from one year to the next. Annual variability in green biomass within the traning sites will influence the supervised classification and the amount of area identified by the classifier as severely degraded. To normalize this variability, we analyzed the outcome based on a four-year period rather than on single years. A geographic information system (GIS) model was developed to overlay the classification outputs from each set of four consecutive years (1988–1991, 1989–1992, and 1990–1993) in order to determine the areas consistently being classified as severely degraded (similar to the training sites). It was assumed that the areas most consistently identified as severely degraded would be most similar to the training sites in terms of cover, composition, and condition. Areas that were identified as severely degraded only in occasional years are in somewhat better condition and show signs of possible improvement as conditions change.

Field Verification

Field reconnaissance was conducted to qualitatively asses the triage assessment. Roads were overlaid on the model output images and areas identified as severely degraded were visited. Cover and composition were visually estimated and an assessment of degradation status was made by estimating the size and frequency of unvegetated patches and soil surface erosion features (rill, litter trains, lag gravels etc.) At the boundaries of severely degraded communities, as identified by the modeling technique, we looked for changes in cover and/or composition. As we traveled to the randomly selected 'degraded' sites, we looked for other areas that appeared to be degraded but were not classified as degraded. Quantitative data were

Table II

Rainfall (in mm) chaacteristic of the study region for the years that AVHRR imagery were classified. Winter-spring rainfall includes precipitation from November through April. Summer rainfall includes rainfall from May through September. Data are from the Jornada Experimental Range

Season	1988	1989	1990	1991	1992	1993
Winter-spring	99.6[a]	44.0	37.9	94.2[a]	199.6[a]	104.4[a]
Summer	198.7	216.7	166.8	268.9	281.7	149.5
Annual total	343.4	279.1	249.7	433.1	406.1	246.4

[a] Indicates sufficient winter-spring moisture for development of ephemeral flora.

collected on 7 sites by pace (step-point) transects (Bonham, 1989) to provide data on cover of shrubs, grasses, and bare ground.

Field data were also collected at the Ft. Bliss Military Reservation on sites classified as degraded in at least 3 of the 4 years in the 1988–1991 composite. We measured plant cover by species using the line intercept method (Bonham, 1989) on three 100 m lines set at random compass directions from a center point located in the center of randomly selected pixels. These data were compared with the average data for the three training sites in mesquite coppice dune systems.

4. Results and Discussion

The application of the sliding window of four year groupings of images (1988–1991, 1989–1992, 1990–1993) produced three maps with units that were classified the same as the irreversibly degraded reference sites (Figures 4–6). Land units that were classified as degraded in all four years and those classified as degraded in three of the four years retained essentially the same boundaries in most areas for all of the years included in the study. There were large changes in boundaries of 'degraded' patches in other areas. The area exhibiting the largest changes in boundaries was the area of mesquite coppice dunes in the lower right corner of Figures 4–6. This area is on the Ft. Bliss military reservation and was an armored vehicle training area during the Gulf War of 1990–1991. This activity had considerable impact on the coppice dune system and was probably partially responsible for the large changes in reflectance from this area. This result raises a cautionary warning for the application of this technique for triage assessment. Severely degraded areas can exhibit short-term changes in reflectances as a result of human activities. In the triage assessment approach described in this paper, such changes in reflectance would be interpreted as degraded ecosystems improving to an at-risk or partially degraded classification.

The correlations among areas classified as irreversibly degraded in all four years of a combined sampling period varied between 42.6% and 84.3% (Table IIIa).

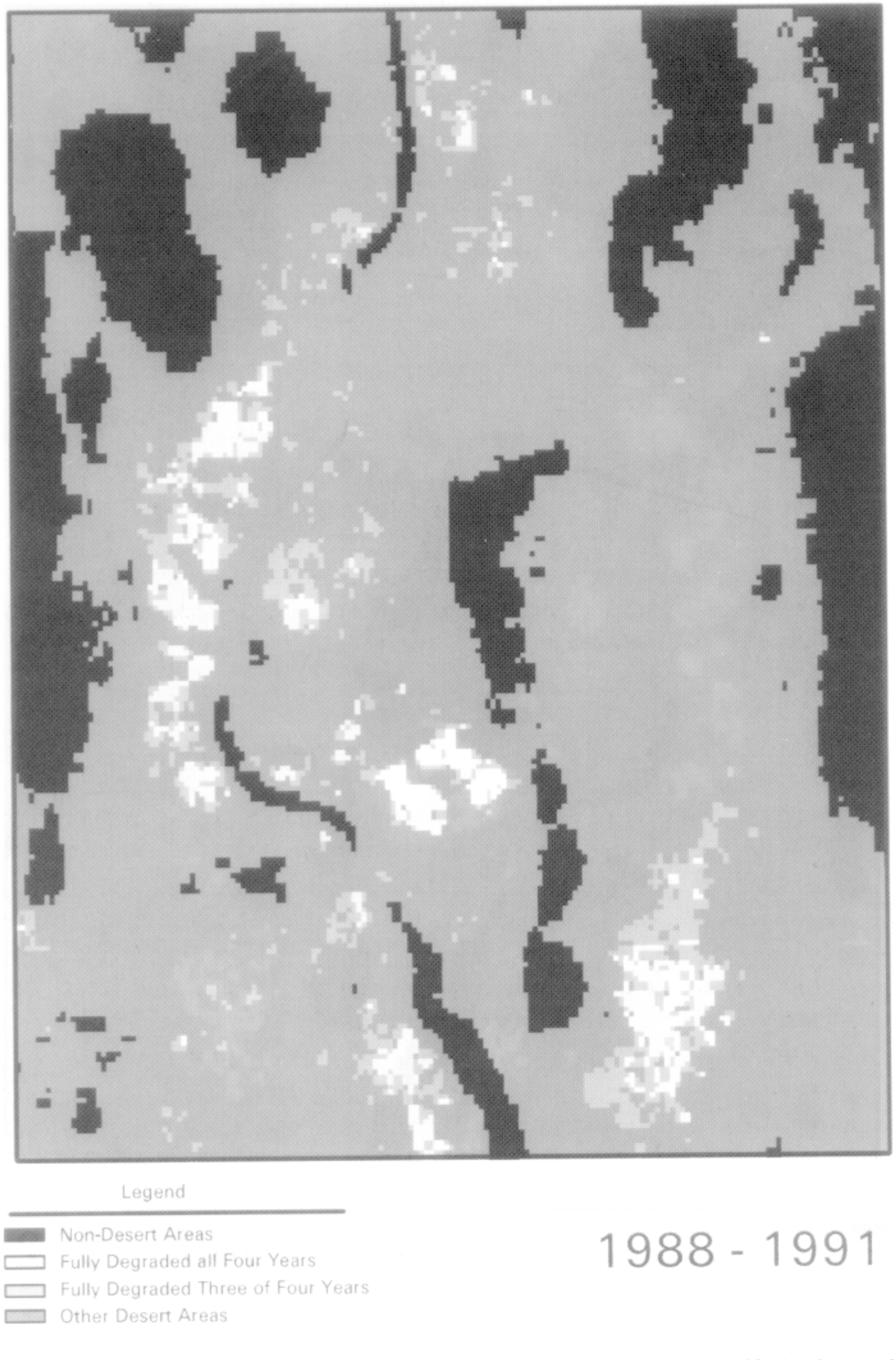

Figure 4. Composite image for the growing seasons of 1988–1991 for areas classified as irreversibly degraded in 3 of 4 years and 4 of 4 years of the composite.

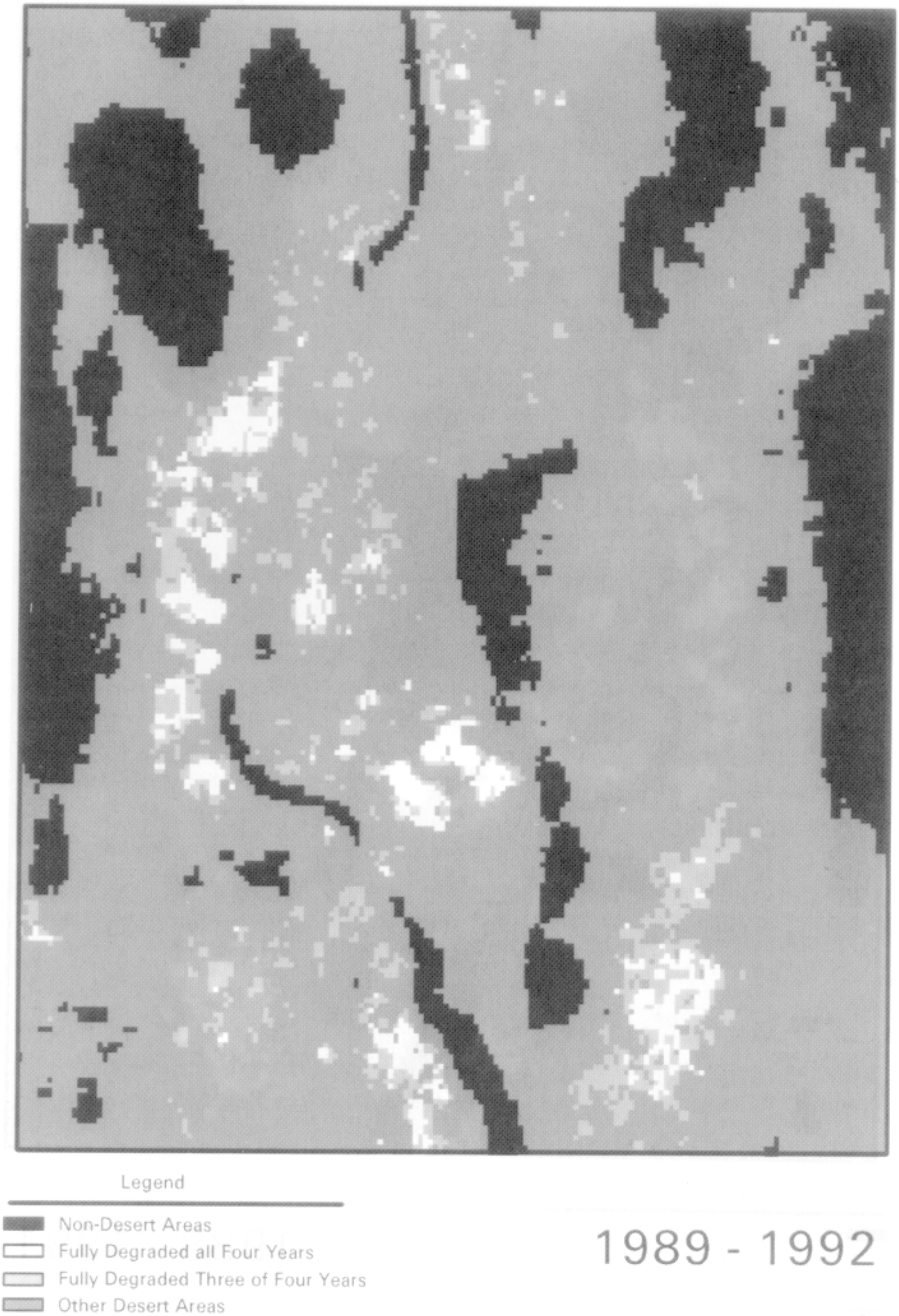

Figure 5. Composite image for the growing seasons of 1989–1992 for areas classified as irreversibly degraded in 3 of 4 years and 4 of 4 years of the composite.

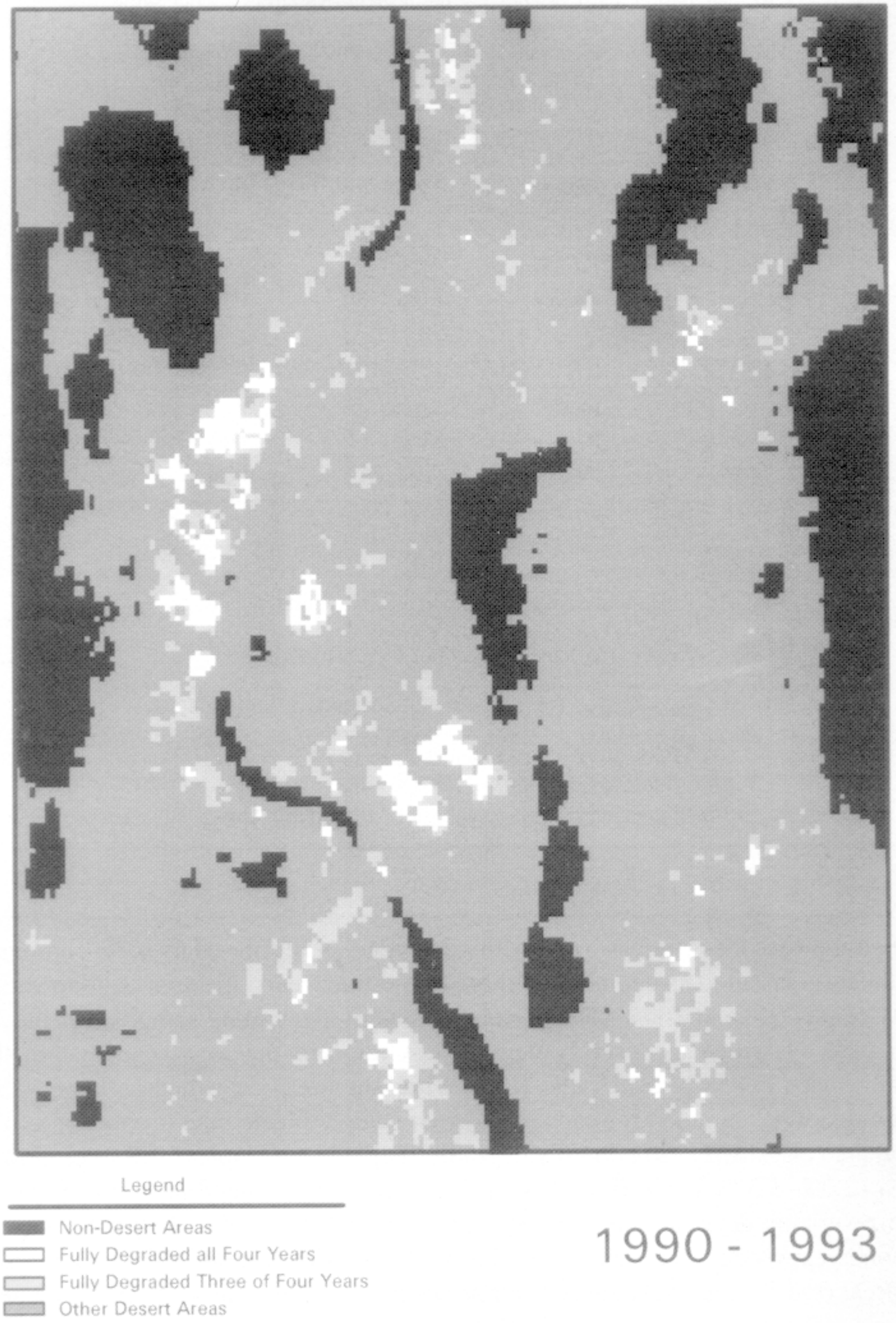

Figure 6. Composite image for the growing seasons of 1990–1993 for areas classified as irreversibly degraded in 3 of 4 years and 4 of 4 years of the composite.

Table IIIa

Cross-tabulation matrices showing the persent overlap in area classified as irreversibly degraded based on images for the year blocks examined. The year blocks are identified by the years and the number in parentheses indicates the number of years within a year block that a pixel was classified as severely degraded. (4) indicates classified all 4 years, (3) indicates at least 3 of the years in the block

Year block	1988–1991 (4)	1989–1992 (4)	1990–1993 (4)
1988–1991 (4)	100%	71.2%	42.6%
1989–1992 (4)	76.5%	100%	55.0%
1990–1993 (4)	70.3%	84.3%	100%

Year block	1988–1991 (3)	1989–1992 (3)	1990–1993 (3)
1988–1991 (3)	100%	100%	83.9%
1989–1992 (3)	100%	100%	100%
1990–1993 (3)	84.3%	84.3%	100%

Table IIIb

Total number of hectares and percent of total area of rangeland classified as irreversibly degraded in 4 of 4 years (four) and at least 3 of 4 years (three)

Year block	Four	Three
1988–1991	122 089 (3.3%)	194 326 (5.2%)
1989–1992	113 619 (3.0%)	14 775 (5.7%)
1990–1993	74.052 (2.0%)	185 977 (5.0%)

When the sites classified as irreversibly degraded in all four years were combined with sites classified as degraded in three of the four years, the area overlap varied between 84.9% and 100%. The correlations were low among sample year blocks for areas classified as severely degraded in three of the four years within the year block (26.3%–59.8% Table IIIa). When the areas classified as irreversibly degraded were summed for each of the year sample blocks, the proportion of the total area classified as irreversibly degraded yielded some large differences in total area (2.0%–3.3%, Table IIIb). When those areas were added to areas classified as irreversibly degraded three of the four years in the same block, the differences among year blocks were reduced (Table IIIb). The variation in extent and location of areas classified as irreversibly degraded using multiple years of AVHRR imagery suggests that there are problems with the accuracy of the classification. Accuracy assessment of multi-year imagery would require collection of quantitative data at a larger number of sites than we sampled in the image vertification effort in this research. This result also indicates the need to identify the climatic characteristics

Table IVa

Vegetative cover of sites used for quantitative field vertification of AVHRR-NDVI triage assessment. The classification is based on the number of years a site was classified as severely degraded. Values in the table are percent cover based on step-point estimates

Classification	Bare soil (%)	Shrub cover (%)	Grass cover (%)
(1) 3 of 4 years	90.4	9.1	0.5
(2) 3 of 4 years	87.0	12.5	0.5
(3) 3 of 4 years	67.0	10.7	22.3[a]
(4) 4 of 4 years	85.0	7.1	9.05[a]
(5) 4 of 4 years	90.0	8.5	1.5
(6) 4 of 4 years	85.0	13.5	1.5
(7) 4 of 4 years	84.3	14.2	1.5

[a] Sites located in topographically heterogeneous areas. High grass cover in drainages where soil accumulated in the bottoms.

Table IVb

Vegetative cover variation of sites classified as degraded at a minimum of 3 of 4 years in the 1988–1991 composite for the Ft. Bliss Military Reservation compared to the average cover values for the three mesquite coppice dune training sites

Classification	Bare soil (%)	Shrub cover (%)	Grass cover (%)	Proposis cover
(1) 3 of 4 years	57.3	40.5	2.2	27.6
(2) 4 of 4 years	64.6	35.4	0.075	32.1
(3) 4 of 4 years[a]	62.2	37.9	0.0	34.8
(4) 4 of 4 years	65.0	35.0	0.0	30.5
(5) 3 of 4 years[a]	72.8	26.7	0.6	21.0
(6) 3 of 4 years[a]	62.6	34.3	3.2	29.0
Dune sites	66.9	31.8	1.3	28.7

[a] Indicates area not classified as irreversibly degraded in the 1990–1993 composite.

of years that can be used to make accurate assessments of the extent and locations of irreversibly degraded areas.

The analysis of scenes from 1990–1993 produced the fewest pixels that classified as irreversibly degraded. Extremely wet winters in 1991, 1992 and 1993 (94.2 mm–199.6 mm) resulted in three consecutive years of luxuriant growth of winter–spring annual plants. Annual plants growing within the coppice of dunes and around the edges of creosotebush shrubs should have a dramatic effect on the NDVI values for the early summer. In addition, annual plant occurrences in the northern Chihuahuan Desert is dependent upon the availability of nutrients as well as winter-spring moisture (Gutierrez and Whitford, 1987). Thus annual plant occurrences are patchy, and the spatial patterns and locations of patches change from year to year depending upon the local availability of moisture and nutrients. While independent site statistics were generated for each year from each training site, the abundance and spatial variability of spring annuals caused more variability in the landscape during years with wet winter–spring seasons. These anomalous spring seasons resulted in upredictable classification outcomes since we did not have field data on the spatial extent and pattern of annuals for each year. The sliding window approach used in this analysis minimized the effect of the anomalous wet springs. However, when such an anomaly occurs in three consecutive springs (an extremely low probability event), a four-year window is unable to adequately compensate and the aerial extent of the severely degraded sites is poorly delineated. With further analysis and acquisition of several additional years of satellite imagery, this problem could be overcome. For instance, implementation of a five- or six-year sliding window would minimize the possibility of having one time window dominated by years exhibiting wet winter-spring seasons.

Two of the sites at which we collected quantitative data demonstrated one problem in using AVHRR imagery for triage assessment. In these cases the areas were classified as degraded in 3 of 4 years or in 4 of 4 years (Table IVa). However, when we visited those sites and collected data on transects, there was considerable grass cover on those locations. Both sites were in topographically variable areas with hill slopes and ridges occupying 2 to 3 times the area of the flats between ridges. The hill slopes and ridges were barren with sparse shrub cover (<15%) and no grass cover in the intershrub spaces. The soil surface of the hill slopes and ridges had a cover of rocky lag which is an indicator of recent soil loss. The depressions between hills supported a high cover of perennial grasses (primarily black grama, *Bouteloua eriopoda*, and burro grass, *Scleropogon brevifolia*). The other sites that we visited were on relatively flat terrain and none of the degraded sites had more than 15% shrub cover or more than 1.5% perennial grass cover (Table IVa). The data from these sites demonstrate one of the problems with using AVHRR for triage assessment. The early morning pass of the satellite sees the low areas in topographically heterogeneous areas as shadows. The vegetation on areas that are shadowed yield lower reflectance; therefore affecting the overall signal that is mixed to give the NDVI value for the 1.1 km^2 pixel. Knowing that topographically diverse areas are likely to suffer from mis-classification, the topography of a study area can be an overlay on the classified imagery. Topographically complex areas would therefore have to be sampled on the ground or analyzed using satellite imagery with a mid-day overpass because of the potential error due to shadows.

The vegetative cover and composition on the Ft. Bliss coppice dune sites was nearly identical with that at the training sites (Table IVb). There was large variation in area classified as degraded on Ft. Bliss. Some of the sites were classified as non-degraded in the 1990–1993 composite (Figures 4–6). The 1990–1993 composite did not reflect the condition of that area based on the limited ground data that we collected. Potential reasons for that mis-classification were the military activities as discussed previously and/or variations in the responses of different areas of this coppice dune field to winter–spring rainfall and the development of ephemeral vegetation.

Using the road overlay on the vegetation (degradation map) we found that transitions between mapped units were readily detectable on the ground. Frequently there were transitions at fence lines demarking the grazing lease of one rancher from that of another. The coincidence of these transitions on our mapped units made us confident that most of the map units were correctly classified and mapped.

For the northern Chinuahuan Desert rangelands, we hypothesize that better triage assessments may be made using imagery from a single year with optimal rainfall–vegetation response characteristics. In order to clearly distinguish the early spring peak in greenness of the mesquite in coppice dunes and the creosotebush shrublands, it is obviously advantageous to have imagery where that signal is not compromised by the addition of a signal from herbaceous spring annuals. In shrub environments, the densities of spring herbaceous annuals is greatest under the canopies of shrubs (Parker *et al.*, 1982) and can contribute to an increase in NDVI. Winter–spring herbaceous annuals require relatively high rainfall beginning in November and continuing through February (Kemp, 1983, and unpublished data). By selecting imagery for years when the November through February rainfall is below average, it is possible to get clear resolution of the boundaries of irreversibly degraded sites from a single year's imagery without the confounding variable of reflectance from annual plants.

The year for which we had data that showed minimal production of winter–spring ephemerals was 1989. When the regional analysis was done on the 1989 imagery alone (Figure 7), the fully degraded class contained 8508 pixels (10 295 km^2). This is 27.5% of the desert rangeland area in the basin or 21.8% of the entire region. This percentage is very different from the average of 5.3% of the entire area classified as severely degraded from the composited images (Table IIIb). According to the U.S. Department of Interior figures, 15% to 18% of New Mexico desert grassland range is in poor condition (Holechek, 1992). This is lower than the figure of 21.8% classified as severely degraded in this study based on the imagery for 1989. However, the composite images classified much less of the area as severely degraded rangeland.

Using the boundaries of the mesquite coppice dune patches and creosotebush shrubland on the Jornada Experimental Range and of the coppice dune fields at Ft. Bliss Military Reservation for reference, it appears that the 1989 image taken alone may povide the best assessment of the extent location of creosotebush shrubland and mesquite shrubland in the region. By selecting imagery from a year in which winter rainfall is insufficient for development of winter–spring ephemeral flora, the problem of adding the ephemeral flora signal to that of the C_3 shrubs is avoided. However, the resulting map includes areas which have high cover of shrub canopies and also sufficient grass and herbaceous plant cover that rangeland improvement is possible with suitable management strategies. A single year image consequently over-estimates the extent of the secerely degraded areas and is not recommended for triage assessment.

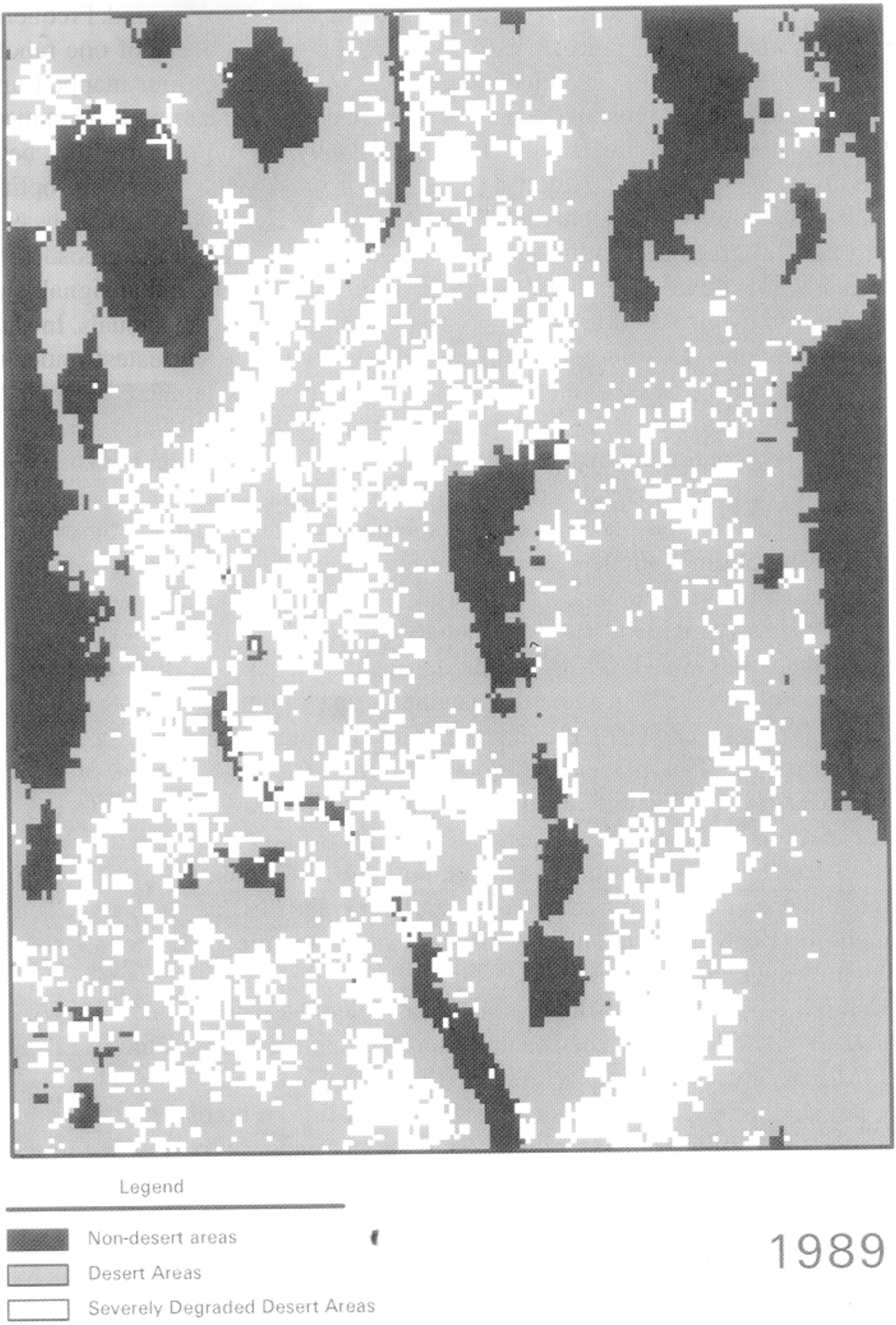

Figure 7. Areas classified as irreversibly degraded based on NDVI values for the 1989 growing season.

The multiple year analysis provided a conservative evaluation of the extent of irreversibly degraded rangeland. This study demonstrates that the variability in seasonal patterns of production of annual plants may cause some areas that are severely degraded to be classified at as risk. Because the single year analysis that was selected on the basis of low winter rainfall and absence of spring annuals overestimated the extent of severely degraded rangelands, the units that we classified differently by these two approaches possibly represent the areas most at risk to transition to irreversibly degraded. The resolution of this question will require extensive and intensive accuracy assessment.

The comparison of year blocks demonstrates one of the most valuable aspects of the approach used here for triage assessment. In each of the year blocks, there were core areas that classified as severely degraded in at least three of the four years of that year block. The variation in the boundaries of the areas classified as severely degraded resulted from variations in cover/productivity that differed from the training sites. Since the training sites have been documented as irreversibly degraded (Herbel *et al.*, 1983; Whitford, 1995), those core areas share the characteristics that make them not feasible to restore or improve. The more extensive areas delineated in the 1989 image obviously share some but not all of the characteristics of the training sites. This difference is clearly seen in images from years with different rainfall patterns and amounts. The areas that are not included in the core severely degraded areas as defined by the year blocks analysis are 'at risk' for futher degradation and should be the areas receiving attention from land managers.

It is important to emphasize that the triage assessment approach outlined in this paper has been tested only for Chihuahuan Desert rangelands. While we are confident that this approach will work in other ecosystems, the ecosystem characteristics that indicate irreversible degradation are different for each system. Because of those differences, the data derived from the imagery will have to be selected to provide clear boundaries for the degraded areas. It may also be possible to assess the proportion of and location of land areas that are at risk for transition to the irreversible degraded state but that assessment potential requires additional analysis of AVHRR imagery and extensive ground data for accuracy assessment.

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