Time Series Satellite Data to Identify Vegetation Response to Stress as an Indicator of Ecosystem Health

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Abstract—One measure of health in an ecosystem is the response of that ecosystem to an environmental perturbation (such as rain) over time. Healthy and unhealthy systems may have different phenological response patterns. Grassland and shrubland sites were selected, and metrics derived from temporal profiles of vegetation index values from Advanced Very High Resolution Radiometer satellite data from 1987 through 1993. The temporal profiles show that the vegetation types may be statistically discriminated, and metric values demonstrate different responses to rainfall.

The term "ecosystem health" is widely used by scientists, land owners and managers, and policymakers at all levels to indicate a condition that is both aesthetically and economically acceptable. However, the expression has varying meaning for different interest groups, and the criteria by which it is assessed often vary from one ecosystem to another. Before health can be judged, for any ecosystem, it is necessary to identify indicators such as keystone species, and acceptable ranges for measured values of these indicators (Haskell and others 1992). Haskell and others (1992) argue that each ecosystem has a specific suite of indicators, however, we propose that certain ecosystem structural and functional characteristics may be used as measurements of health.

Net primary production has been identified as the most important carbon cycle variable for quantifying and comparing biological activity across regions and biomes (Running 1990), and is an indicator of ecosystem function. Changes in ecosystem structure, such as biomass or leaf area index, may be identified and monitored using spectral radiance data acquired by sensors on-board satellites or aircraft to determine species composition and vegetation patterns (Mouat 1995). The repeated measurement of an ecosystem variable from the synoptic perspective of an aircraft or satellite sensor permits ecosystem analyses at varying spatial and temporal scales, facilitating the analysis of ecosystem dynamics which are reflected in temporal changes in vegetation. Studies of shrub and forest communities (Law and Waring 1995; Yoder and Waring 1994) demonstrate that vegetation operating under severe environmental constraints caused, for example, by prolonged drought, will show lowered photosynthetic rate and therefore decreased productivity throughout the year. This might be an indicator of ecosystem health.

Based upon assumptions that numerous stressors affect arid ecosystems, including climate, grazing, herbicide use and recreation, and that vegetation composition and cover is a response to ecosystem stress, it is hypothesized that satellite data may be used to evaluate ecosystem response through the use of a vegetation index such as the Normalized Difference Vegetation Index (NDVI). Ecosystems respond in different ways to stressors, such as drought, depending on their structural and functional integrity. Vegetation composition and cover may be seen as a response to stress, either natural as in the case of climate, or anthropogenic, in origin. Vegetation responds to water stress caused by severe or prolonged drought by closing leaf stomata, which decreases conductance of carbon dioxide from the atmosphere into leaf tissues and limits the plant's ability to absorb carbon through photosynthesis (Schulze and Hall 1982).

The research objective specific to the study reported here was to statistically evaluate the suitability of a suite of metrics derived from NDVI temporal profiles for discriminating variation in response to climate between mesquite and grassland systems.

Methods

An experimental design was developed which involved the selection of sites in both grassland and mesquite dominated areas, and verification of their vegetation and soils homogeneity using spectral response of vegetation during periods of maximum photosynthetic activity. Values for NDVI for each site at approximately biweekly periods during the growing season were extracted from satellite imagery, and plotted as annual temporal profiles for a seven year period from 1987 through 1993. The profiles were smoothed using a locally weighted regression, and metrics characteristic of phenological response calculated for each site for each year of the study. Values for the metrics were correlated with seasonal and annual rainfall totals, and the differences in photosynthetic response between vegetation types statistically validated.

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Satellite Data

The Advanced Very High Resolution Radiometer (AVHRR) is carried on-board the NOAA series of satellites, orbiting the earth twice daily on a sun synchronous schedule (NOAA 1986). Ground based radiance is collected in five spectral bands: red (Channel 1, 0.58-0.68 um), near infrared (Channel 2, 0.72-1.10 um), mid infrared (Channel 3, 3.55-3.93 um) and two thermal infrared bands (Channel 4, 10.3-11.3 um and Channel 5, 11.5-12.5 um) from pixels measuring 1.1 x 1.1 km in size when the satellite is at a nadir viewing angle. With heterogeneous land cover types, the 1.1 km pixel size results in the integration of varying spectral responses, which makes it suitable for regional scale studies. At these scales, the AVHRR has been used to monitor herbaceous cover in Botswana (Prince and Tucker 1986), correlate vegetation biomass with rainfall patterns in the Sahara (Malo and Nicholson 1990) and assess biological diversity for California (Walker and others 1992). Mouat (1995) hypothesizes that the spatial scale of AVHRR is directly applicable to the examination of ecosystem health, based on the premise that it is appropriate for the ecosystem processes involved (Malingreau and Belward 1992).

These studies typically use the Normalized Difference Vegetation Index (NDVI):

$$NDVI = (NIR - RED) / (NIR + RED)$$

where NIR is reflectance in near infrared wavelengths and RED is red waveband reflectance. The NDVI minimizes the effects of topography and atmosphere (Holben and Justice 1981), requires no prior knowledge of ground conditions, and is sensitive to the amount of photosynthetically active vegetation present (Myneni and others 1992; Tucker 1979).

With synchronous data collected on a daily basis, the AVHRR offers the most appropriate data set for temporal studies, and cloud-free images are usually available at 10 to 15 day intervals for the western U.S. Temporal profiles of NDVI or other indices capture and quantify differences in the extent and intensity of physiological activity throughout the growing season. Vegetation temporal response has been used to detect the effects of short-term drought in New Mexico, based on the differences between wet (1988) and dry (1989) years (Peters and others 1993), and to observe phenological differences between natural and cultivated vegetation throughout North America (Goward and others 1985). Seasonal range conditions in Senegal were monitored using NDVI time-series data (Tappan and others 1992), and Malo and Nicholson (1990) found that spatial and temporal patterns of NDVI closely followed rainfall in west Africa.

Site Selection Criteria

A prerequisite for the selection of a study area was current vegetation with variation in composition and cover which had originated as a uniform vegetation type. The Jornada Experimental Range (JER), near Las Cruces, New Mexico, comprises a mixture of vegetation types, having experienced an increase in shrub species and decrease in area occupied by perennial grasslands since the first vegetation survey in 1858 (Buffington and Herbel 1965). In addition, the JER has maintained climatic and land-use records since 1915, which is critical for a historical perspective on climatic variability. Covering an area of over 40,000 hectares, the JER is within the Chihuahuan Desert, ranges in elevation from 1,260 to 2,833 m, and has a mean annual precipitation of 247 mm (Agricultural Research Service 1994). Soils contain little organic matter, and root and water penetration are limited by a thick caliche layer often over 2 m in thickness (Agricultural Research Service 1994).

According to the work of Buffington and Herbel (1965), the western portion of the JER originated as perennial grassland, although it is now a spatially diverse mixture of mesquite dominated shrubland, grassland, and combinations of both vegetation types. This area met the site selection criteria for the project, and four sites were located in mesquite dominated areas, and another four in grassland areas in the western portion of the JER (fig. 1), thus providing a replication of study sites for purposes of statistical analysis.

Evaluation of Site Homogeneity

In order to compensate for satellite drift of up to one pixel in any direction, it was necessary for study sites to be spectrally homogeneous over a 3 x 3 km area. This homogeneity was established from spatial variance of reflectance in red and near infrared wavebands using imagery from the Landsat Multispectral Scanner (MSS) with a pixel size of 80 x 80 m. MSS images for April and August were chosen to capture the periods of maximum photosynthetic activity for mesquite and grassland communities respectively. The area of the eight study sites and four less homogeneous sites (as controls) was clipped from each image, and red and near infrared waveband reflectance index values were calculated for aggregates of 81 MSS pixels in 9 x 9 pixel matrices to approximate 1.1 km AVHRR pixels. The among pixel variance for the vegetation index values for the 16 aggregated pixels provided a measure of site homogeneity. An *a priori* coefficient of variation of 10% was chosen as the minimum value for site homogeneity, and study sites met this criteria.

The Department of Geography at New Mexico State University was able to provide AVHRR High Resolution Picture Transmission (HRPT) images for the JER, covering the period 1987 through 1993. Preprocessing of the AVHRR data was carried out by New Mexico State University, and extraction of the NDVI values for the study sites was done at the Desert Research Institute. Values for AVHRR red and near infrared reflectance were calculated from cloud-free imagery acquired at 10 to 15 day intervals throughout the annual active photosynthetic cycle and used to calculate NDVI. An area slightly larger than each 3 x 3 km study site was clipped from each AVHRR image, the NDVI value for the center pixel of the matrix was extracted, and the resulting values were plotted against time to give a temporal profile of NDVI response. Some early spring and late summer values for NDVI were higher than expected (the "terminator effect", Goward and Peters, personal communication, 1994). As a result these data were excluded from the study, resulting in nine to 12 data points between April 29 and September 19 for each study year.

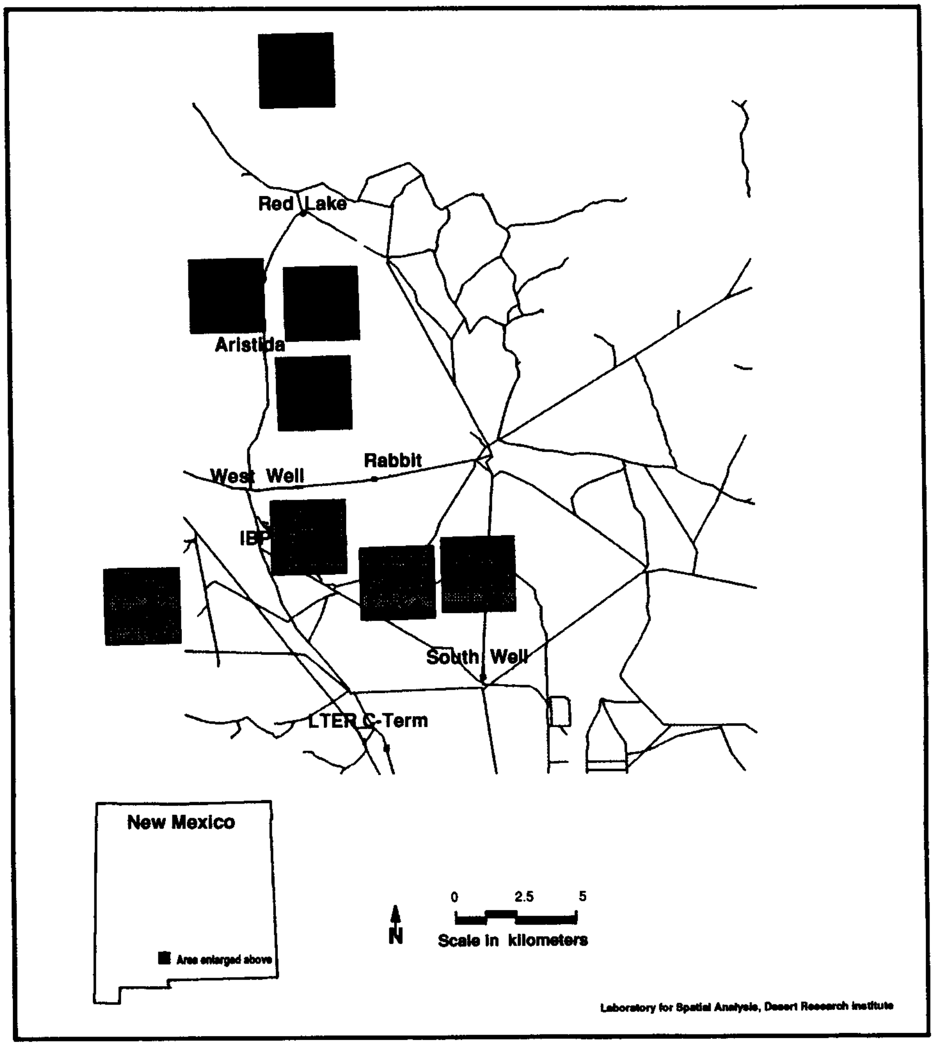

Figure 1—Location of study sites (squares) and rain gauges (named locales) at Jornada Experimental Range. Dark gray sites are mesquite dominated, pale gray sites are grassland areas.

NDVI Analysis

A daily profile of NDVI response or trend over time at a given site was felt to characterize the distinct pattern or shape of the NDVI response on the site. Various metrics could then be derived from the NDVI time profile with the potential to distinguish the patterns or shapes of the profiles between the two vegetation types. Since NDVI data were available for only 9-12 dates at each site, a daily profile of NDVI response for each site had to be estimated from these 9-12 NDVI observations.

An implementation of robust locally weighted regression or LOESS (Cleveland 1979; Cleveland and Devlin 1988) was used to estimate the NDVI profile for each of the sites in each of the years. LOESS is a nonparametric function to describe the relationship between two variables.

In the case of the NDVI profiles the NDVI response was assumed to be some unknown function ("g") of time:

$g(T_i)$ or $NDVI_i = g(T_i) + e_i$

where i = 1,2, t and e(i) is random error, and T is time. The NDVI responses were smoothed as a function of time in a moving fashion analogous to how a moving average is computed for time series, however, a locally weighted linear or quadratic regression is used for the smoothing rather than a simple average.

The LOESS smoothed fit illustrated for one of the grassland sites in 1989 (fig. 2) includes the twice standard error band around the smooth fit which corresponds roughly to 95% confidence limits for the nonparametric smoothing (Hastie and Tibshirani 1990). NDVI values for each observation over the 1989 growing season were aggregated for the four grassland and four mesquite sites respectively, showing significant variations in phenological response between the two vegetation types (figs. 3 and 4).

A number of metrics derived from NDVI temporal profiles have been proposed as indicators of ecosystem identification, behavior and response to perturbation, (Samson 1993; Reed and others 1994). These derived metrics include total NDVI response measured as an integration of the NDVI profile, seasonally integrated NDVI, duration of NDVI response, maximum NDVI, date of maximum NDVI, rate of NDVI increase during the greenup periods, and rate of NDVI decrease during the brown-off periods.

Six primary metrics calculated from the yearly profiles at each of the eight sites are illustrated in figure 5. They are total NDVI response, or integrated area under the profile

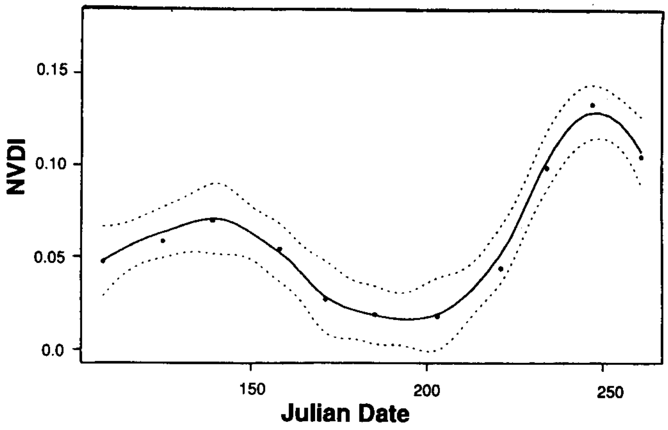

Figure 2—NDVI temporal profile LOESS fit for a grassland site with NDVI values plotted as points, and twice standard error limits shown as a dotted line.

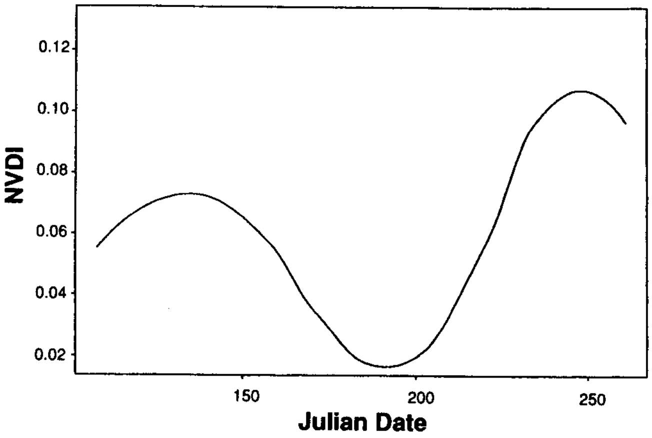

Figure 3—LOESS smoothed fit for aggregated site NDVI data for grasslands in 1989.

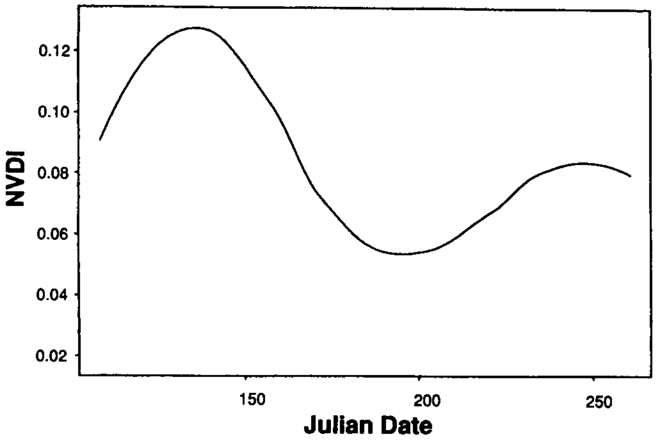

Figure 4—LOESS smoothed fit for aggregated site NDVI data for mesquite in 1989.

with NDVI above 0.03; duration of NDVI response, or number of days with NDVI above 0.03 between April 29 and September 19; NDVI response between April 29 and June 15; NDVI response between August 1 and September 19, maximum NDVI; and date of maximum NDVI. Examples of NDVI metrics, also given for 1989, are shown in table 1.

The climate data used for the analysis comprised previous year total rainfall, previous winter rainfall (October-January), current year spring rainfall (February-April), current year (May and June) rainfall, current year summer rainfall (July-September), current year total rainfall, and degree days above 5 °C between January 1 and May 15 for the current year. The rainfall data were collected at separate rain gauges for the mesquite sites and the grassland sites resulting in distinct rainfall values for the two types of sites. The degree days were common for the two vegetation types.

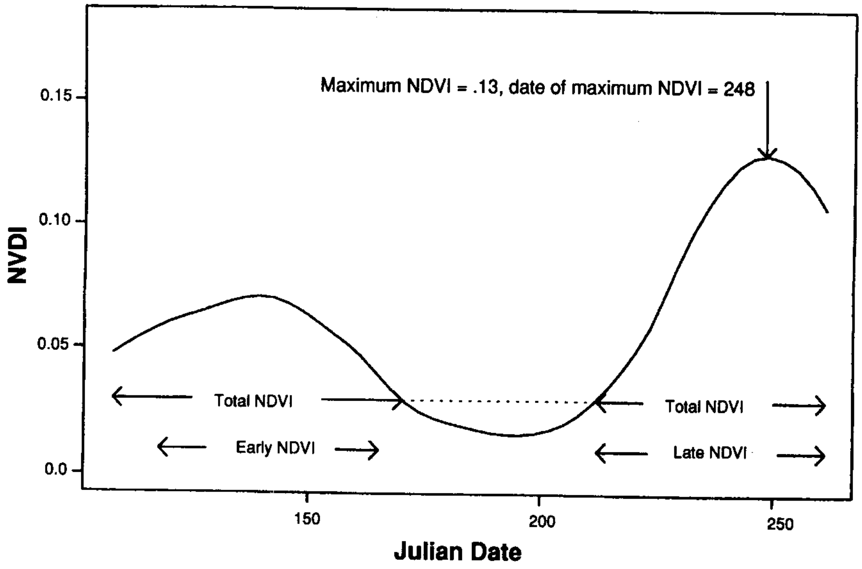

Figure 5—LOESS smoothed NDVI profile showing criteria for deriving the metrics.

Table 1—Values for NDVI metrics for 1989.

Site[1]	Early[2]	Late[3]	Maximum NDVI[4]	Maximum date[5]	Duration[6]
1	3.459	7.358	0.081	132	121
6	2.893	9.682	0.130	248	110
7	3.263	10.328	0.137	247	117
8	2.954	10.459	0.149	245	121
2	5.072	8.341	0.128	140	153
3	6.038	9.485	0.150	139	153
4	5.934	9.066	0.141	135	153
5	5.037	8.848	0.118	138	153

[1] Sites 1, 6, 7, and 8 are grassland and sites 2, 3, 4, and 5 are mesquite dominated.

[2] The "early" variable is the integrated NDVI profiles from April 29 to June 15.

[3] The "late" variable is the integrated NDVI profiles from August 1 to September 19.

[4] Value of maximum NDVI.

[5] Julian date of maximum NDVI.

[6] Number of days in which NDVI ≥ 0.03.

Table 2—Rainfall covariates for which the NDVI metrics had a statistically significant positive (increased) response to increased rainfall (indicated with "+").

	Rainfall				
	Previous year	Previous winter	Feb-April	May-June	July-Sept
Grassland					
Total NDVI	+				+
NDVI duration		+	+		+
Spring NDVI	+				
Summer NDVI	+			+	+
Maximum NDVI	+		+		
Date of max NDVI					+
Mesquite					
Total NDVI	+		+		
NDVI duration			+		
Spring NDVI	+		+		
Summer NDVI	+		+		
Maximum NDVI	+		+		
Date of max NDVI		+			+

The generalized linear model (McCullagh and Nelder 1989) was used to estimate the relationships between the NDVI metrics and the climate covariates in order to determine whether the NDVI metrics for mesquite and grassland systems had differential responses to climate. The generalized linear models allow for a broad range of statistical error model families in the parameter estimation routine, and as such are not limited to the normal distribution error model.

The response variables for the generalized linear model were the NDVI metrics. The independent variables or covariates included the study design variables of vegetation type (grassland or mesquite) and replicate sites within each vegetation type as well as the climate covariates. The rainfall covariates were included in the model with separate regressions for each of the vegetation types since there were separate rainfall measures for each vegetation type. Degree days was entered as a common regression for both vegetation types since the degree days covariate was common to both types. The analysis for regression of the NDVI metric on rainfall covariates was conducted to determine whether the regression coefficients were significantly different for the two vegetation types or of similar value for the two vegetation types.

Results

The results of the best fitting models for each of the vegetation types are shown in table 2, indicating those covariates to which the NDVI metrics had a statistically significant positive response (for example, increased). In no instance was the "degree days" variable significantly related to any of the NDVI metrics.

In general the patterns of positive responses of the two vegetation types to rainfall have some similarities and some differences. This study was in part designed to identify those NDVI metrics, if any, which show differential responses for grassland and mesquite sites to climatic variables as an indicator of relative health. The primary difference between the two vegetation types was manifested by NDVI metrics for the mesquite sites which were predominantly responsive to spring rainfall, and the same NDVI metrics for grassland sites which were predominantly responsive to summer rainfall. The NDVI metrics for the two vegetation types responded similarly to total rainfall in the previous year. Total, early, and late NDVI response as well as the maximum NDVI metrics all increased with previous year rainfall.

Total NDVI response for grassland sites increased with summer rainfall, whereas the total NDVI response for mesquite sites increased with spring rainfall.

The duration of NDVI response increased with spring rain for both grassland and mesquite sites. This was probably a function of prolonging the growing season. However, the duration of NDVI for grassland sites also increased with previous winter and summer rain, while the duration of NDVI response for mesquite sites was significantly related only to spring rainfall.

Early NDVI response (April 29 to June 15) for mesquite sites increased with previous year and spring rainfall, while the early NDVI response for grassland sites was significantly related only to previous year rain. This may have been a result of the response of a minor C_3 shrub, grass and forb component.

Late NDVI response (August 1 to September 19) for grassland sites increased with May-June and summer rainfall, whereas the late NDVI response for mesquite increased only with spring rainfall.

The maximum NDVI for sites of both vegetation types increased significantly with spring and previous year rainfall. As might be expected, the date of maximum NDVI was significantly later with increased summer rainfall for the grassland sites, but for mesquite sites the date was significantly later with increased previous winter rainfall as well as increased summer rain.

Summarizing the differences in the response of NDVI metrics to rainfall variables it was found that total NDVI response for grasslands increased with summer rain, whereas the total NDVI response for mesquite increased with spring rain. The duration of NDVI response was prolonged in grasslands by increased previous winter, spring, and summer rainfall, whereas it was prolonged only by spring rainfall in the mesquite. The early NDVI response of grasslands increased only with previous year rainfall, but the early response of mesquite also increased with spring rainfall. The late NDVI response of grasslands increased with May-June and summer rainfall whereas the late response of mesquite increased only with spring rainfall. The date of maximum NDVI for grasslands occurred later only with increased summer rainfall, but the maximum NDVI for mesquite also occurred later with increased previous winter rainfall. Maximum NDVI relationships to rainfall were similar for the two vegetation types since both increased with previous year and spring rainfall.

Conclusions

Of primary significance in the results is the demonstrated statistical discrimination, in a site replicated study, between the two vegetation types with metrics derived from their NDVI response. Equally important, the results are consistent with differences in biological responses of the two vegetation types to rainfall patterns found in other studies (Donovan and Ehleringer 1994; Neilson 1986; Van Devender in press).

The effective statistical discrimination of two distinct vegetation types with satellite derived metrics provides the potential framework for a technique useful to discriminating these ecosystem characteristics in other settings.

NDVI metrics derived from temporal profiles are a measure of phenological response, and may indicate primary productivity. Changes in values for individual metrics, or the suite of metrics, occurring over a period of several years, might indicate changes in ecosystem structure, and may be used to monitor the condition, or health, of the system.

We have hypothesized that one measure of health in an ecosystem is the response of that ecosystem to an environmental perturbation (such as rainfall) over time. A healthier system may have a different phenological response pattern than the less healthy system and will maintain this pattern over time. The less healthy system will have a phenological response pattern which will diverge from the healthier one. The research reported illustrates a landscape which was predominantly grassland in the early 19th century. Following human disturbance, much of the grassland was replaced by shrubs (dominantly mesquite). We feel that the shrub-dominated areas took advantage of winter rains and "green up" earlier in the year. The AVHRR NDVI temporal response profiles support this observation. Continuing analysis will help to elucidate these relationships and either support or reject the hypotheses.

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