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A Protocol for Retrospective Remote Sensing–Based Ecological Monitoring of Rangelands

Robert A. Washington-Allen,[1] Neil E. West,[2] R. Douglas Ramsey,[3] and Rebecca A. Efroymson[4]

Authors are [1]Research Assistant Professor, Department of Environmental Sciences, University of Virginia, Clark Hall, 291 McCormick Rd, Charlottesville, VA 22904-4123, and Adjunct Professor, Department of Geography, University of Tennessee, 304 Burchfiel Bldg, Knoxville, TN 37996; [2]Professor and [3]Associate Professor, Department of Forest, Range, and Wildlife Sciences, Utah State University, Logan, UT 84322; and [4]Senior Research Staff Scientist, Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box 2008, Bethel Valley Rd, Oak Ridge, TN 37831.

Abstract

The degree of rangeland degradation in the United States is unknown due to the failure of traditional field-based monitoring to capture the range of variability of ecological indicators and disturbances, including climatic effects and land use practices, at regional to national spatial scales, and temporal scales of decades. Here, a protocol is presented for retrospective monitoring and assessment of rangeland degradation using historical time series of remote sensing data and catastrophe theory as an ecological framework to account for both gradual and rapid changes of state. This protocol 1) justifies the use of time-series satellite imagery in terms of the spatial and temporal scale of data collection; 2) briefly explains how to acquire, process, and transform the data into ecological indicators; 3) discusses the use of time-series analysis as the appropriate procedure for detecting significant change; and 4) explains what reference conditions are appropriate. Landsat data have been collected and archived since 1972, and include complete coverage of US rangelands. Characteristics of land degradation can be retrospectively measured for a nearly 33-year trend using surrogate remote sensing–based indicators that correlate with changes in life-form composition (time series of thematic maps), declines in vegetation productivity (vegetation indices), accelerated soil erosion (soil indices), declines in soil quality (piospheric analysis), and changes in landscape configuration (time series of thematic maps). Aspects of 2 retrospective studies are presented as examples of application of the protocol to considerations of the land use impacts from military training and testing and ranching activities on rangelands.

Resumen

El grado de degradación de los pastizales en los Estados Unidos de América es desconocido debido al fracaso del monitoreo tradicional de campo para capturar el rango de variabilidad de los indicadores ecológicos y disturbios, incluyendo los efectos climáticos y prácticas de uso de la tierra, a escalas espaciales de regional a nacional y escalas temporales de décadas. Consecuentemente, es presentado un protocolo para el monitoreo retrospectivo y la evaluación de la degradación de los pastizales usando series de tiempo históricas de sensores remotos y la teoría de catástrofe como un marco ecológico para cuantificar tanto los cambios graduales como los rápidos del estado del pastizal. Este protocolo: 1) justifica el uso de series de tiempo de imágenes de satélite en términos de escalas espacial y temporal de colección de datos; 2) explica brevemente como adquirir, procesar y transformar los datos en indicadores ecológicos; 3) discute el uso del análisis de series de tiempo como un procedimiento adecuado para detectar cambios significativos; y 4) explica que condiciones de referencia son apropiadas. Datos de Landsat han sido colectados y archivados desde 1972 e incluyen una cobertura completa de los pastizales de Estados Unidos de América. Las características de la degradación de la tierra pueden ser medidas retrospectivamente para una tendencia de casi 33 años usando indicadores de remplazo basados en sensores remotos que se correlacionan con cambios en la composición de las formas de vida (series de tiempo de mapas temáticos), disminuciones en la productividad de la vegetación (índices de vegetación), erosión acelerada del suelo (índices de suelo), disminución de la calidad del suelo (análisis piosférico) y cambios en la configuración del paisaje (series de tiempo de mapas temáticos). Se presentan aspectos de dos estudios retrospectivos como ejemplo de la aplicación del protocolo para consideraciones de los impactos del uso de la tierra en entrenamiento y pruebas militares y actividades de rancho en los pastizales.

Key Words: catastrophe theory, ecological indicators, land degradation, Landsat, trend

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At the time of the research, the senior author was Research Staff Scientist, Environmental Sciences Division, Oak Ridge National Laboratory, PO Box 2008, Bethel Valley Rd, Oak Ridge, TN 37831, and Postdoctoral Fellow, Intermountain Region Digital Image Archive Center, Department of Forest, Range, and Wildlife Sciences, Utah State University, Logan, UT 84322.

Correspondence: Dr. Robert A. Washington-Allen, Department of Environmental Sciences, University of Virginia, Clark Hall, 291 McCormick Rd, Charlottesville, VA 22904-4123. Email: washingtonra@mac.com

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INTRODUCTION

The condition and trend of rangelands in the United States at subregional to regional scales is unknown today (National Research Council 1994; The H. John Heinz III Center for Science, Economics, and the Environment 2002; West 2003a, 2003b). Historical and contemporary monitoring and assessment protocols are primarily based on the collection of point samples of vegetation and soil attributes at local spatial and limited temporal scales. The collected point samples are statistically interpolated or aggregated to larger spatial scales and compared to reference sites (e.g., relict or lightly grazed areas) to draw conclusions about change in rangeland condition and trend. However, the use of this space-for-time field-sampling approach at subregional to national spatial scales has proven inadequate due to excessive economic costs, the spatial and temporal heterogeneity of landscape dynamics, and the incompatibility of sampling objectives, methods, data, and conclusions among different land management agencies (West et al. 1994; West 2003a, 2003b).

Furthermore, very few field-based surveys have been conducted at sufficient temporal scales to account for historical variability in measured indicators, to detect either gradual or threshold change in indicators, or to separate land management activities from climatically driven landscape responses (Washington-Allen 2003; West 2003b). A suggested solution is to increase the sampling frequency to at least 2 times the temporal scale of the driving climatic phenomena (Magnuson 1990). For example, the fauna and flora of rangeland ecosystems are constrained by El Niño-Southern Oscillation (ENSO) events that have a 2- to 7-year return interval, thus requiring monitoring from 4 to 15 years (Holmgren and Scheffer 2001). Very strong ENSO events have longer repeat intervals. In the last 25 years, 2 major ENSO events have occurred in 1982–1983 and 1997–1998 (Bonan 2002). However, few sites at subregional to national spatial scales were monitored for this length of time or longer (Magnuson 1990).

West (2003b) recognized the spatial and temporal scale-dependence of assessment tools for rangeland monitoring and recommended that research at subregional to regional scales incorporate geographic information systems and satellite remote sensing data, as well as new ecological concepts from landscape ecology and complex systems science, including dynamical systems analysis, hierarchy, and catastrophe theories. The National Research Council (1994) concluded: "there is a need for inexpensive inventory, classification, and monitoring methods with links to current ecological theory."

Tueller (1989) provided an overview of remote sensing technologies and current and possible applications more than 15 years ago in an invited paper to the *Journal of Range Management* (now *Rangeland Ecology & Management*). The paper explained the bright future of remote sensing technologies and how they could be used to monitor and assess rangeland condition and trend. More recently, Hunt et al. (2003) demonstrated how remote sensing could be used to provide the kinds of products (e.g., forage availability and quality) that have utility for, and would be adopted by, land managers. Yet despite the promise of this technology, few private organizations, federal agencies, and nongovernmental organizations have a formal protocol for using historical and emerging remote sensing technologies for monitoring and assessment of rangeland condition and trend. Consequently, this paper presents a simple protocol for using historical archives of Landsat satellite imagery to retrospectively monitor and assess rangeland degradation.

METHODS

The proposed protocol proceeds by 1) discussing the characteristics and advantages of Landsat imagery for retrospective studies; 2) describing how indicators are selected in relation to land degradation; 3) explaining how catastrophe theory and the states-and-transition model provides the theoretical context for characterization and inference of the behavior of ecological indicators; 4) demonstrating how Landsat data are acquired, processed, and transformed to indicators; 5) discussing how to spatially and temporally validate the behavior of ecological indicators; 6) explaining the appropriate statistics to use for analyzing trend and significant change from reference conditions; and 7) presenting 2 example applications that use aspects of the protocol and had the purpose of detecting the ecological impact of land use activities, particularly military training and testing and commercial grazing, on rangelands.

Landsat Characteristics

The National Aeronautics and Space Administration's (NASA's) Landsat program in cooperation with the US Department of the Interior was begun in 1972, and has collected data approximately every 14 days for the last 33 years, and continues to do so (Goward and Masek 2001). Landsat Multi-Spectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM+) collect spectral and textural data at a pixel resolution ranging from 15 to 79 m, and at a spatial extent from paddock to near global coverage. Landsat TM and ETM+ provide a spectral resolution (sensed part of the electromagnetic spectrum) of 7 bands from 450 nm to 12 500 nm. These bands alone or in combination are sensitive to water turbidity, vegetation growth and cover, and soil/plant moisture. Additionally, relative to ground data collections, acquisition of remotely sensed data is cost-effective (Bastiaanssen 1998).

Definition of Degradation and Derived Indicators

Rangeland scientists and managers define physical rangeland degradation in terms of parameters related to vegetation and soil (Pickup 1989; Milton et al. 1994). Land degradation is defined as:

- A change in plant species, life-form, or physiognomic composition that is contrary to management goals (Archer 1989);
- Decrease in plant cover, density, productivity, or some other plant parameter or measurement of attributes (Reeves et al. 2001; Washington-Allen et al. 2004a, 2004b);
- A reduction in soil quality (e.g., nutrient loss) (Perkins and Thomas 1993);
- Accelerated soil erosion (Pickup 1989); and

- Changes in landscape composition and configuration (Turner et al. 2001).

Landscape composition refers to the proportion of different land units or patch types (e.g., shrub or grass dominated patches on a landscape), and configuration refers to both structure and spatial pattern. For rangelands, the fundamental patch type is the ecological site defined as "a distinctive kind of land with specific characteristics that differs from other kinds of land in its ability to produce a distinctive kind and amount of vegetation" (US Department of Agriculture Natural Resources Conservation Service [NRCS] 2003). Pattern refers to the change in spatial organization or arrangement of ecosystem characteristics viewed as patches within a mosaic (e.g., a shrub vegetation patch within a bare soil and grassland mosaic). Structure refers to changes in the shape, size, and number of patches (Turner et al. 2001).

Indicators that are diagnostic of these attributes of rangeland condition and trend can be derived from the spectral and textural characteristics of Landsat imagery. For example, the spectral characteristics of Landsat in relation to the spectral reflectance characteristics of surface features allows the development of biophysical models such as the Normalized Difference Vegetation Index (NDVI), which relies on the difference in percent reflectance of incident near infrared (NIR) and red (R) energy from leaf tissue. NDVI has been significantly correlated with ecological indicators that are commonly collected in the field, including plant cover and phytomass (Sellers 1985). The vegetation signal-to-noise ratio of NDVI is reduced by soil background reflectance in rangelands. Consequently, the soil-adjusted vegetation index (SAVI), a form of the NDVI, was specifically developed to increase the vegetation signal in rangelands (Huete 1988). SAVI is calculated as:

$$\mathrm{SAVI} = [(\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R} + \mathrm{L})]*(1 + \mathrm{L}) \qquad [1]$$

where L is a constant that varies between 0 and 1 (usually taken to be 0.5) with the soil background. Like NDVI, SAVI data, when collected in a multitemporal mode, is a surrogate of the response of vegetation attributes such as phytomass or cover to disturbance.

A second indicator is the soil stability index, which measures a change in the erosional state of a surface on the basis of how topographic position and erosion state affect reflectance (Pickup and Nelson 1984). Third, when the spatial distribution of former land use practices such as grazing, military bivouac areas, and petroleum exploration and production is unknown, SAVI is capable of detecting their localized impacts at piospheres (Washington-Allen et al. 2004b). A piosphere is an indicator of change in the soil chemistry (quality) and vegetation response in the area surrounding a resource (e.g., a water source, oil well, bedding ground, etc.) (Perkins and Thomas 1993). Fourth, a time series of satellite-derived thematic maps of plant physiognomy can be used to detect compositional changes (Washington-Allen 2003). Finally, various landscape metrics in programs such as FRAGSTATS (McGarigal and Marks 1995) can be used on these thematic maps to measure changes in landscape configuration, including clumping of patches and fragmentation (Turner et al. 2001; Olsen et al. 2005).

Theoretical Basis of Rangeland Monitoring

Rangeland landscapes are complex systems that are primarily constrained by anthropogenic activities, fire, herbivory, and various edaphic and climatic factors that limit water availability (Lockwood and Lockwood 1993; Allen and Breshears 1998; Rietkerk et al. 2004). Ecological indicators are developed with knowledge of how different attributes of vegetation and soils respond to these constraints. The conceptual basis of vegetation response in rangelands was based on the linear, gradual, and equilibrium dynamics of Clementsian plant succession (Clements 1936; West 2003b). However, this model does not account for the catastrophic behavior that has been observed in rangelands (e.g., Archer 1989; Lockwood and Lockwood 1993; Rietkerk et al. 1996; Allen and Breshears 1998; Washington-Allen 2003) and is reflected in the states-and-transition model that has since replaced it (Westoby et al. 1989). Because the complex interactions of constraints such as grazing, fire, and climate change can produce multiple stable states (gradual, linear, nonlinear, and threshold behavior), catastrophe theory has been proposed as the mathematical formalism that underlies the states-and-transition model (Lockwood and Lockwood 1993). Figure 1 is a graphical cusp catastrophe adaptation of states-and-transition or threshold models (or both) presented by Lockwood and Lockwood (1993), Rietkerk et al. (1996), and Scheffer et al. (2001). In the model, each state on the manifold surface (e.g., A in Fig. 1) is the remotely sensed indicator response (e.g., a change in life-form composition from shrubland to grassland on the vertical z-axis) of an ecological site to driving variables on the x (grazing pressure) and y (soil moisture availability [El Niño– and La Niña–driven wet and drought periods]) axes. The protocol assumes that the landscape of interest has been stratified into ecological sites by a decision rule/deductive (Creque et al. 1999) or an inductive (Jensen et al. 2001) spatial modeling approach. Analysis of the response of ecological indicators to constraints (e.g., stocking rates and precipitation) by fitting them to a catastrophe model will provide an assessment of landscape condition and trend (Scheffer et al. 2001; Washington-Allen 2003).

To further illustrate, Figure 1 predicts the spatial response of landscape composition and configuration to particular disturbances (Washington-Allen 2003; Rietkerk et al. 2004). This prediction indicates which particular landscape metrics should be used with a time series of life-form thematic maps to detect a significant change. For example, during conditions of intense grazing and repeated droughts, a rangeland landscape is predicted to catastrophically shift from a clumped homogenous perennial grassland state (Fig. 1, B) to a state of dispersed islands of dense shrubland (Fig. 1, C; Washington-Allen 2003; Rietkerk et al. 2004). In the absence of grazing and increased water availability, the opposite trend is expected to occur (Fig. 1, D to F to E). Consequently, a landscape metric such as contagion, which measures both the clumping and dispersion of a landscape's patches, should be used (Turner et al. 2001).

Data Processing and Standardization

Interannual time series of Landsat imagery from 1972 to the present can be acquired from the United States Geological Survey's (USGS's) Earth Resources Observation System Data Center (EDC) in Sioux Falls, South Dakota, using the EarthExplorer

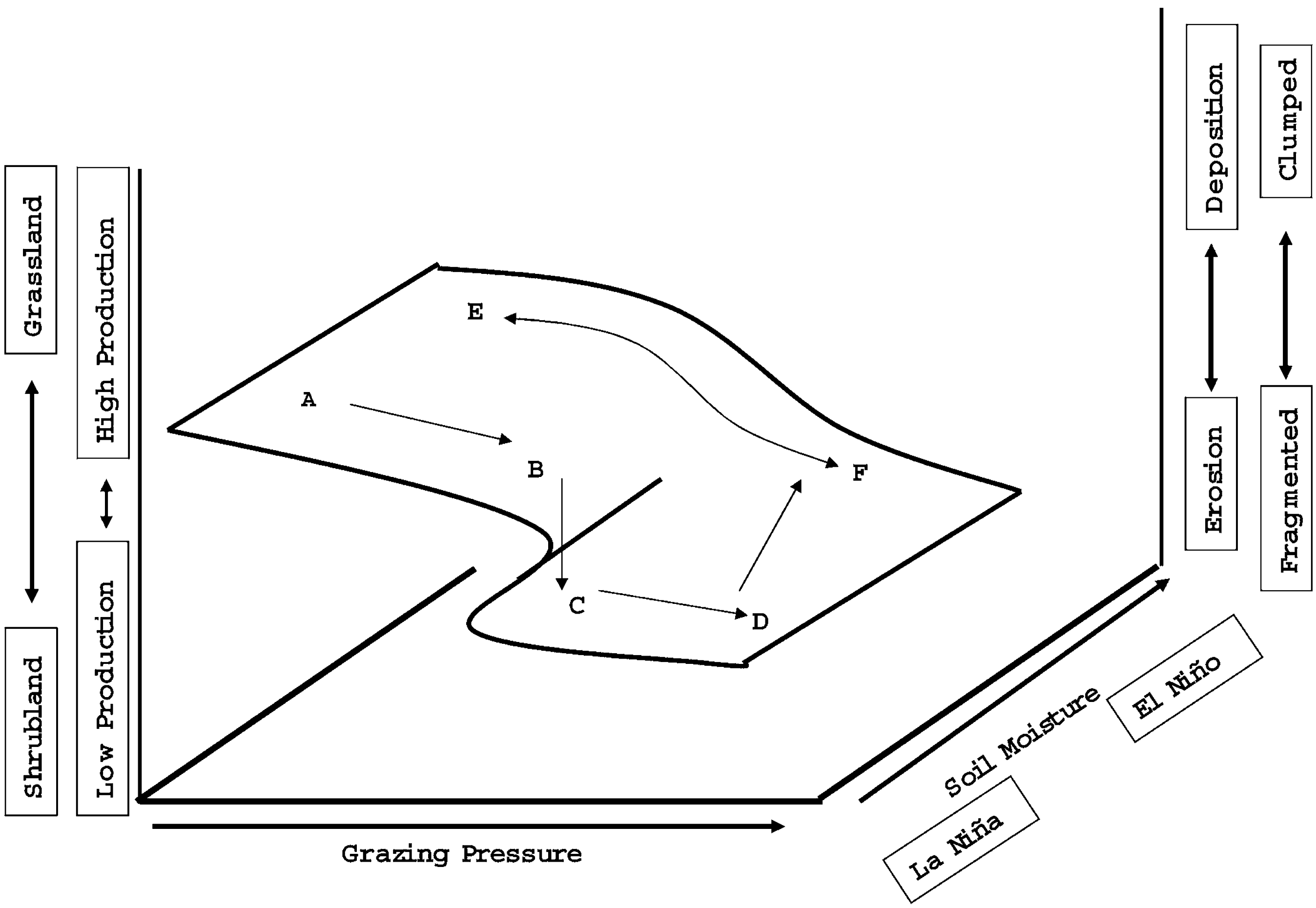

Figure 1. The cusp catastrophe model represents the response of vegetation characteristics, including physiognomic composition, productivity, connectivity, and erosion to both grazing pressure and soil water availability. Soil moisture levels are expressed in terms of the expected ecohydrological response of rangelands to El Niño and La Niña events. A catastrophic response (B to C) occurs at high grazing pressure and intense drought conditions. This trajectory is irreversible and displays hysteresis unlike the trajectory from E to F, which is both gradual and reversible. The trajectory from D to F was induced by a very wet event that provided the resources for a landscape to recover to more productive conditions.

Web site (http://edcsns17.cr.usgs.gov/EarthExplorer/). Limited time series of free satellite data can also be downloaded for rangelands from the University of Maryland's Global Land Cover Facility (GLCF: http://esip.umiacs.umd.edu/index.shtml) and from Utah State University's Intermountain Region Digital Image Center (IRDIAC: http://earth.gis.usu.edu). Also, MSS data from 3 dates (thus a triplicate of usually 1973, 1986, and 1991) that were produced for the North American Landscape Characterization project (Lunetta and Sturdevant 1993) are available at reasonable cost ($45 per triplicate compact disc compared with a single MSS scene at $200 to $1 000 in the recent past) from EDC (http://edc.usgs.gov/products/satellite/nalc.html). However, direct comparison of these processed data sets with each of the other data sets discussed herein requires additional work to achieve a standardized data set. EDC provides the user with image quality selection criteria from which anniversary images with minimum cloud cover should be selected. It is helpful to use both a Walter-Lieth climate or ombrothermograph and plant phenological diagram to make the image selection. Phenological diagrams may be derived from archives of 1-km resolution NDVI satellite data at reasonable cost from the Advanced Very High Resolution Radiometer or Moderate Resolution Imaging Spectroradiometer. A rule of thumb is to select dry season scenes during periods of low antecedent rainfall that are photosynthetically active just before the plant senescent period of phenology. These scenes are selected because of the relatively clear atmospheric conditions, the ability to use greenness vegetation indices, and the consequential ability to examine the perennial and thus persistent vegetation cover (Pickup 1990).

Since 1972, 7 Landsat platforms with 3 different radiometers including Landsat MSS, TM, and ETM+ have been deployed. Because of the differing formats, 5-bit (Landsat MSS) and 8-bit TM, and the differing pixel resolutions of 15 m to 79 m, respectively, images are: 1) rectified and resampled to a common map projection and resolution, 2) standardized by conversion to exoatmospheric reflectance values using Landsat's postlaunch calibration gains and biases (e.g., Markham and Barker 1986), and 3) atmospherically corrected using either an absolute or relative correction procedure for multitemporal imagery (e.g., Jensen 1996). Rectification of satellite imagery now commonly uses the USGS's high-resolution digital orthophotographs. EDC also provides rectified data as a standard. The procedures for standardization of the satellite time series can be quite time-consuming. Consequently, a considerable amount of time and thought has gone into consideration of techniques to automate the standardization and atmospheric correction procedures. Tools and documentation for standardizing a Landsat time series can be found at this Web address: http://earth.gis.usu.edu/landscapetools.html.

The standardized satellite image time series is then converted to a time series of ecological indicators, such as SAVI, using map algebra or vegetation life-form (or both), and land cover thematic maps by either a manual (somewhat onerous) or automated classification procedure (e.g., a maximum-likelihood cluster analysis).

Ground Truth/Validation

The time series of remotely-sensed ecological indicators such as SAVI can be validated for precision and accuracy of measurement in space and time by comparison to appropriately scaled field samples or "ground truth" correlates (e.g., vegetation cover or phytomass) that are contemporaneous with the image time series. Second, in order to capture spatial variability, the field measures must be surveyed along an environmental gradient. For example, in the early 1990s, the US military instituted the Land Condition and Trend Analysis (LCTA) monitoring program, which stratified field plots into sampling units based on the homogeneity of their remotely sensed surface reflectance (West et al. 1994). Another example is a 1980 study that occurred in the sagebrush steppe portion of the Great Basin in northeastern Utah, at Deseret Land & Livestock Ranch (DL&L) (a case study that will be further discussed). Percent canopy cover had been estimated for 18 sections (1.6 km $\times$ 1.6 km) from field plot data that had been collected by the NRCS. These data were compared to 1980 mean SAVI values for the 18 sections using regression analysis. Field and satellite data were significantly correlated with SAVI ($r = 0.96$ and $P = 0.07$) (Washington-Allen 2003). Additionally, comparison was made between mean SAVI and phytomass data from 4 grazing exclosure treatments within 3 paddocks (12 total) that were situated along a moisture gradient. Phytomass data had been collected from 1992 to 1998 (Ritchie and Olff 1999) and had high and significant correlations with SAVI ($r = 0.86$ to 0.96 and $P = 0.001$ to 0.03) in only 3 of the 7 years (Washington-Allen 2003). A multiple regression study showed that significance was based on the annual relative flux of phytomass between life forms, suggesting that 1) caution must be used when applying calibration equations developed in 1 year to other years, and 2) that scale of sampling (i.e., plant life form or plant community), affects calibration. Similar results were found at the Konza Prairie Long-term Ecological Research site by Briggs et al. (1998) for aboveground net primary productivity.

Validation in time is usually accomplished by comparison of the time series of a remotely sensed indicator to a contemporaneous time series of field-collected data. This aspect of the protocol can be problematic, especially for those landscapes for which historical field data are unavailable for comparison in time. Similarly, the field data could be used to calibrate the satellite data, but for both objectives, how the field data were scaled to develop a relationship with the satellite data may become problematic. Contemporary designs for field validation are nested grid approaches, which at the smallest spatial scale, collect field samples within a Landsat TM pixel resolution (30 m) plot and use geostatistical approaches, such as kriging, to extrapolate these data to landscape spatial scales (e.g., Wylie et al. 2002). A similar approach has been used with the military's LCTA data (R. D. Ramsey, personal communication). Validation in time on DL&L was accomplished by comparing the mean phytomass of the 4 exclosure treatments in 1 paddock from 1992 to 1998 to mean SAVI within the exclosures for the same time period. The significant correlation fit was a fourth-order polynomial ($r = 0.67$) with an increasing trend (i.e., as phytomass increased SAVI increased).

Alternatively, when field measurements are not available, then documented historical data on sites where disturbance impacts are known to have occurred can be used to validate the behavior of indices. For example, both the US Bureau of Land Management (BLM) and the NRCS documented fire and erosion events at particular plot sites in their survey records for DL&L (Washington-Allen 2003).

Time series of life-form or vegetation cover maps are validated by conducting an accuracy assessment of the classifications in each year. An accuracy assessment entails comparison of each thematic map to higher-resolution contemporary data, including either ground data or aerial photography (Congalton and Green 1998).

Statistical Analysis of Time Series

The appropriate statistical tools for examination of a time series of measurement indicators is, of course, time series analysis. Characterization of the direction and strength of a trend can be accomplished with regression analysis (Yafee and McGhee 2000). The slope (β) is a measure of the direction of trend (i.e., stable [0], increasing [$+\beta$], and decreasing [$-\beta$]), and both the magnitude of the coefficient of determination (r^2) from a linear or polynomial regression and the significance of the slope are measures of the strength of the trend (Yafee and McGhee 2000). Detection of thresholds in the time series can be simply accomplished using the autocorrelation function (ACF; Turchin and Ellner 2000). The largest, significant ACF usually indicates a threshold and allows delineation of the time series into different period states (Fig. 2).

Assessment is defined here as the inference of the causal mechanisms behind change. In retrospective assessments, the outcome, or the response of ecological indicators has already occurred and, at least after the preceding characterization, is already known. However, a problem for landscape-scale studies is that time series of data for causal factors (i.e., disturbance factors such as land management interventions) are usually not available (an exception may be climate data). An advantage of remote sensing is that it can detect both the presence and the magnitude of some disturbances (e.g., the impact of grazing disturbance is detected by piospheric analysis and the effects of fires, particularly the area and perimeter burned can be detected by Landsat imagery). Second, climatic data, such as precipitation, usually need to be scaled from the point data collected at different weather stations to the spatial scales of the indicators of interest, either by spatial averaging or interpolation. For example, interpolated data sets of precipitation and temperature at various spatial and temporal scales for the United States are now available from a number of sites (e.g., http://www.daymet.org/).

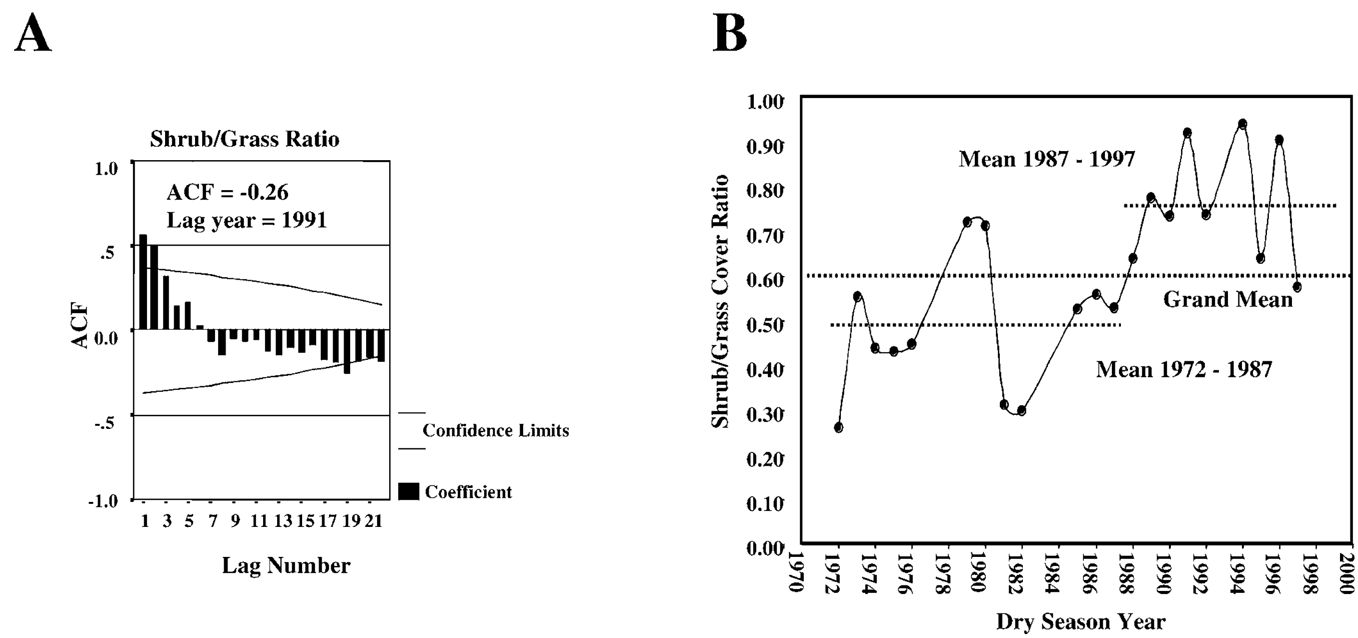

Figure 2. The autocorrelation function (ACF) correlogram plot of the trend in dry season life-form composition (the percent shrub cover divided by the percent grass cover) on the north-central portion of Desert Land & Livestock Ranch, Utah, from 1972 to 1997 (**A**). The ACF detects the lag year when a threshold event occurs and allows delineation of the time series into different physiognomic regimes or states (**B**).

When sufficient management or disturbance data sets are available, correlations with indicators can be determined using a first-order difference regression model instead of an ordinary least squares regression (OLS). OLS regression results between time series must be interpreted with caution because they assume that the mean and variance of a time series are constant over time, and the covariance between 2 time periods depends only on the lag or distance between the time periods; that is, they are stationary. The time series of indicator, disturbance, and climatic variables may contain stochastic trend, and therefore, be nonstationary. Nonstationarity violates the assumption of OLS, which tends to overstate the statistical significance of variables with stochastic trend, otherwise termed "spurious regressions" (Yafee and McGhee 2000). The Dickey-Fuller test statistic (Dickey and Fuller 1979) can be used to detect stochastic trend, but the statistic is not reliable for short time series (17 to 30 observations). One way to reduce the likelihood of a spurious regression is to detrend the time series, thus removing the stochastic trend. This procedure entails transforming the times series using either order of differencing, running means, lags, or some other smoothing operation (Yafee and McGhee 2000). For example, Zhou et al. (2001), in their analysis of an NDVI time series versus temperature and precipitation, used the following first-order difference regression model:

$$\Delta Y - \beta_0 + \beta_1 \Delta X + E \qquad [2]$$

in which ΔY and ΔX are the first differences of X and Y, β_0 and β_1 are the regression coefficients, and E is a stochastic error term (Zhou et al. 2001). The 33-year time series provided by Landsat is a relatively short ecological time series; however, Perry et al. (2000) provide a very good reference for analyzing these data sets.

Benchmark Conditions

Interpretations of the behavior of indicators are dependent on the selection of reference, standard, or benchmark conditions (O'Malley and Wing 2000). A benchmark is a standard by which the value of an indicator can be compared and judged (West 1991). A benchmark can be representative of initial (baseline) conditions, central tendencies (mean, mode, or median), or boundary conditions. Boundary or gradient conditions can be either minimum or maximum conditions, or chosen percentiles or standard deviations from the average (e.g., 95%). Benchmarks can be composite measures of a group of measurement indicators that are ideally independent or uncorrelated with each other. Trend is the overall temporal trajectory of an indicator. Time trends are easily understood by stakeholders and generally are not biased in an obvious way (O'Malley and Wing 2000). The direction of trend can be increasing, decreasing, or stable. However, if a trend is not considered in relation to a reference, the results may be misleading (O'Malley and Wing 2000). For example, the trend of percent vegetation cover of a plant community may be stable, but this stability may be at a level near extinction.

The establishment of a benchmark and the subsequent analysis of trend allows assessment of ecological resilience (i.e., the response and recovery of an ecosystem in relation to a disturbance) (Westman 1985). Consider the mean dry season time series response of SAVI in the Mojave Desert for the Marine Corps Air Ground Combat Center (MCAGCC) in Twentynine Palms, California (Fig. 3). It illustrates the benchmark and other concepts of the protocol that have been discussed in this paper and shows that, consistent with field data, that the Mojave Desert has become wetter since the late 1970s (Beatley 1980; Fig. 3).

It is not the intent of this protocol to make qualitative statements about the condition of a landscape (e.g., "this landscape is in bad shape or good shape"). This is because the choice of a benchmark, as previously discussed, is dependent on dynamic human value systems that vary widely (O'Malley and Wing 2000). However, a benchmark that is commonly used by pastoralists to manage their natural resources is the state of vegetation and soil attributes during severe and repeated droughts, which is a boundary condition (Stafford Smith and Foran 1992). Consequently, the condition of most measurement indicators can be considered in terms of departure of a value of a particular indicator from the value (state) of that indicator during a severe drought period.

RESULTS AND DISCUSSION: CASE STUDIES

Military Base

Camp W. G. Williams (CW) is a Utah Army National Guard training site and occupies 11 500 ha on the southern end of the Great Salt Lake Valley in north-central Utah, 42 km south of Salt Lake City. Oakbrush and pinyon-juniper woodlands dominate the camp at upper elevations, and Great Basin–Colorado Plateau sagebrush semidesert communities dominate at lower elevations (West 1989). The camp is used primarily for military training, which involves heavy vehicle traffic, road construction, combat simulations, and artillery practice. Fire is a major disturbance factor at CW.

The purpose of this study was to use an ecological indicator (SAVI) derived from historical Landsat imagery to assess the effects of military training and testing activities and drought on vegetation from 1972 to 1997. Figure 4 provides a visualization of the changes in vegetation response from 1972 to 1997. Spatial changes in an indicator (SAVI) image can be visualized by thresholding or density slicing the image's continuous values by 2 to 3 times the standard deviation (SD) of the time series. The density slice allows visual discrimination of the spatial distribution of categories across space. If a time series of images are similarly thresholded, the change in number and spatial distribution of categories can be observed through time. For example, an orange swath (indicating lower value SAVI) through 2 main green patches (oak savanna portion of CW) in the northeastern portion of CW was detected in 1995 (Fig. 4). This swath was a fire that occurred on approximately 15% of CW. The lower SAVI values were consistent with the observed location, shape, and effects of the 1995 fire. Besides this validation of SAVI response provided by historical fire data, CW had a limited 6-year (1993 to 1998) time series of LCTA field data that had a similar increasing trend for this period.

The dry season SAVI trend was generally stable from 1972 to 1997 ($r^2 = 0.04$), with abrupt changes in 1994 and 1996 probably due to drought events. The first-order difference SAVI time series was significantly linearly correlated with the Palmer Drought Severity Index (PDSI, $r = 0.44$ and $P = 0.03$). The PDSI usually ranges between -8 and 8 with values > 2 indicating very wet periods and values < -2 indicating severe droughts. We found that the vegetation response to climate is driven by wet and dry periods that are related to ENSO dynamics. Land management data were available in the form of Range Facility Management Support System (RFMSS) data that showed the potential duration of use of a military training area

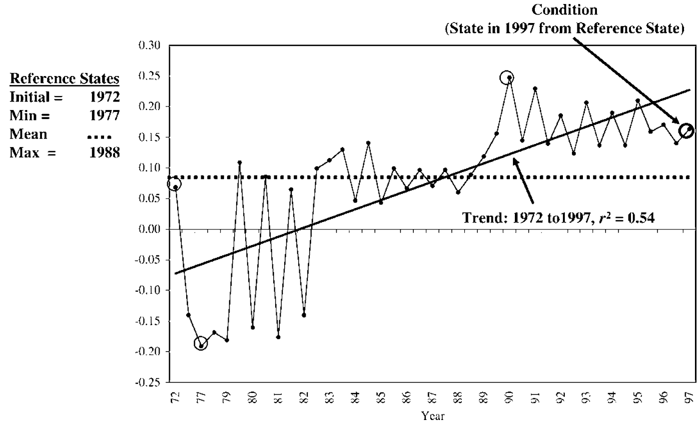

Figure 3. The dry season soil-adjusted vegetation index (SAVI) time series for the Marine Corps Air Ground Combat Center in Twentynine Palms, California, from 1972 to 1997. Monitoring is defined here as the characterization of condition (e.g., SAVI in 1997) and trend (increasing trend, $r^2 = 0.54$) with respect to a number of possible reference states (e.g., the minimum SAVI value in the early 1970s).

by ground troops in relation to SAVI response (Fig. 5). The 2 time series appear to mirror each other and thus have an observable relationship; however, the 3 years of management data are insufficient to permit a statistical assessment of causation (e.g., a first-order difference regression analysis between the 2 time series). Consequently, this study illustrates the need for managers to record time-series data on actual land use activities in order to be able to conduct an assessment of the effects of their activities.

Commercial Ranch

DL&L ranch is located in the Utah panhandle and occupies 88 800 ha, including 6 800 ha of Department of Interior BLM and State of Utah School Trustland sections (Washington-Allen 2003). Mean annual precipitation for the ranch is 240 mm in the northeast and 440 mm in southwest. Mean monthly temperatures range from $-17.1°$ to 27.3°C. Elevations range between 1 889 and 2 700 m. This study focused on 48 000 ha of the DL&L that is primarily covered by sagebrush steppe vegetation (West 1989). DL&L has been commercially grazed since 1891, with sheep use dominating up through the early 1970s. The primary land use on DL&L is currently a mixed commercial cow-calf ranching and wildlife hunting operation.

DL&L has had 3 different owners: Garff, Freed, and Robinson (GFR); Joseph Hotung (JH); and the Ensign Farm Management Group of the Church of Jesus Christ of Latter-Day Saints (LDS), who instituted 3 different grazing systems. These were a continuous grazing system (CGS) from 1953 to 1975, a rotational grazing system (RGS) from 1975 to 1983, and aspects of a short-duration grazing system (SDG) from 1983 to the present, respectively.

The general view is that the success of the contemporary management period compared to the previous 2 periods is due to the increased productivity associated with the 1982–1983 and 1997–1998 ENSO events. Moderate to very strong ENSO episodes have historically featured above- to near-normal precipitation in the Great Basin (Miller et al. 1994). Second, a CGS is expected to have lower production relative to the RGS and SDG systems.

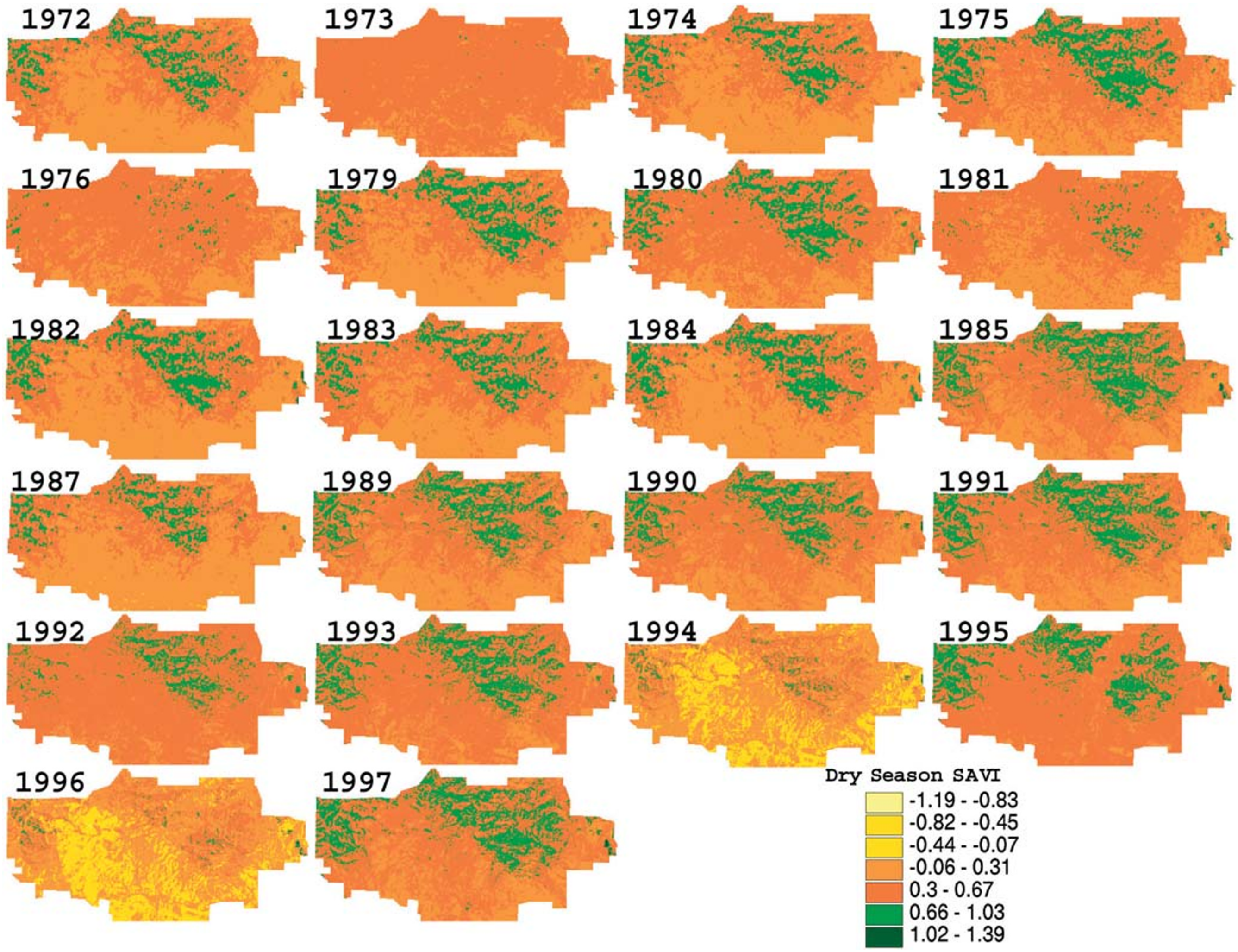

Figure 4. A 2-standard deviation threshold for visualization of the dry season soil-adjusted vegetation index (SAVI) time series (1972 to 1997) for Camp W.G. Williams Army National Guard facility near Draper, Utah.

A times series of seasonal Landsat imagery from 1972 to 1998 were standardized and converted to SAVI for each period (Washington-Allen et al. 2004a, 2004b). The trend of the time series was quantified using regression analysis and further decomposed into the different management regimes (Fig. 6). The grand SAVI mean for the GFR-CGS period from 1972 to 1975 was 0.35 ± 0.06 SD, 0.39 ± 0.05 SD for the JH-RGS period, and 0.40 ± 0.06 SD for the LDS-SDG period. The trend from 1972 to 1975 was linear and stable ($r^2 = 0.32$, $P = 0.18$; Fig. 6). The trend from 1975 to 1983 approximated a quadratic; small in magnitude ($r^2 = 0.07$) and not significant ($P = 0.58$). The trend for the LDS period from 1983 to 1998 was significant ($P = 0.003$), quadratic, and had a moderate magnitude ($r^2 = 0.40$; Fig. 6). Seasonal decomposition of the time series indicated that the dry season SAVI time series had a significant, nonlinear correlation with grazing ($r^2 = 0.63$, $P = 0.047$) and water availability was linearly correlated with 1-year lagged SAVI ($r^2 = 0.62$, $P = 0.006$) (Washington-Allen et al. 2003).

Consequently, the LDS-SDG management period, with the highest mean SAVI and the greatest regression magnitude relative to the other 2 management periods, appeared to be influenced by the 2 ENSO events. The GFR-CGS period actually started in 1953, but within the scope of the satellite data, the GFR period had the lowest mean SAVI value relative to the following management regimes. This appeared to be influenced primarily by the drier periods.

MANAGEMENT IMPLICATIONS

Formal protocols exist for field-based surveys, but these have been criticized for being expensive to conduct and being temporally and spatially limited for monitoring at subregional to national spatial scales (West 2003a, 2003b). Rangeland degradation in terms of changes in plant physiognomy and vegetation parameters (e.g., decreased cover, increased soil erosion, changes in soil quality, and changes in landscape composition and configuration) can be monitored at large spatial and temporal scales using ecological indicators derived from time series of satellite imagery. However, satellite data have been underutilized in the western United States, and when they are used, these data are forced to provide exactly the same

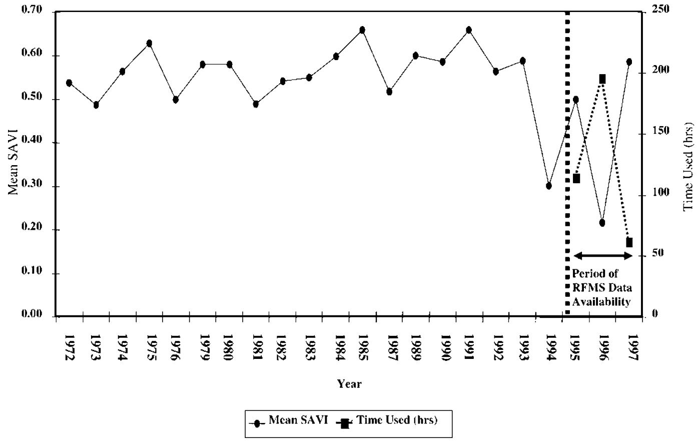

Figure 5. The 1995 to 1997 time series of available Range Facility Management Support System (RFMSS) data of the time spent in hours by military ground troops at a bivouac site at Camp W.G. Williams Utah Army National Guard facility near Draper, Utah, compared with the 1972 to 1997 time series of the mean soil-adjusted vegetation index (SAVI) for that site.

measures derived in the field by calibration to field measures (e.g., Graetz et al. 1988). This approach is not feasible because the costs are as prohibitive as continued field data collection (Graetz et al. 1988; Bastiaanssen 1998).

The Landsat archive has now acquired more than 33 years of synoptic data on rangelands. A synoptic data set does not suffer spatially from inadequate sample size, high variance, difficulties of randomization, and the nonrepeatability and opaqueness (the ability to decompose the summarized data into its component parts) of vegetation and soil sampling on the ground. The 33-year archive is at a temporal scale that does not require the use of space-for-time substitution (i.e., gradient analyses). The historical imagery is available at a sufficient temporal scale to conduct retrospective studies and to replicate the effects of at least 3 major climatic events that have recently affected rangelands: 2 very strong El Niño events and a La Niña event: the great North American drought of 1988 (Riebsame et al. 1991; Holmgren et al. 2001). Because of the various Internet-based NASA-funded archives (e.g., the GLCF and IRDIAC), limited time series of free Landsat data are available to anyone. Consequently, the retrospective protocol presented herein is transparent, repeatable, and portable to a number of rangeland ecosystems. Examples of the protocol have been demonstrated at a number of sites, and 2 of these are presented in this paper.

CONCLUSIONS

Although a number of time series studies with satellite data are present in the literature (e.g., Spies et al. 1994), the demon-

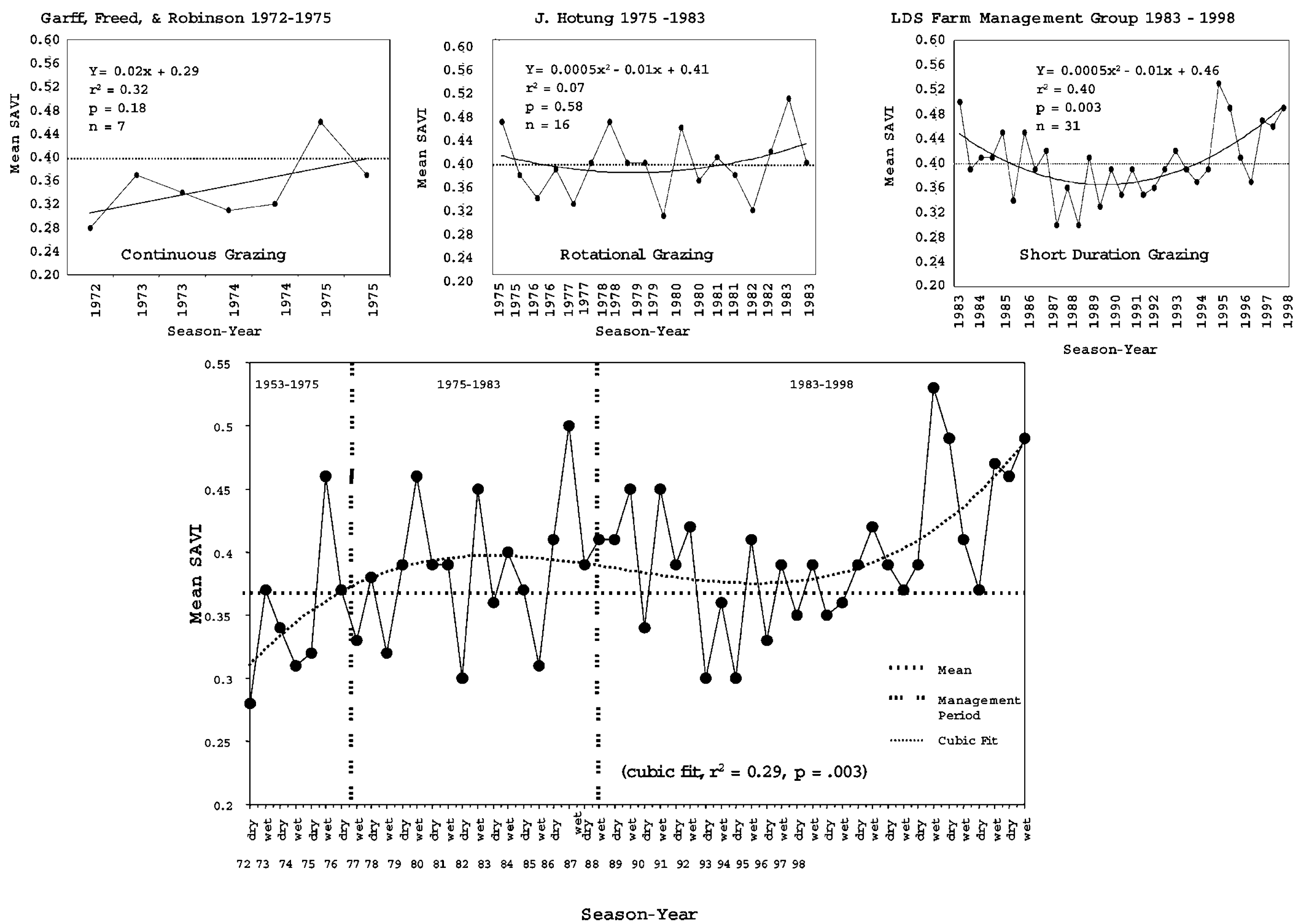

Figure 6. The seasonal wet and dry soil-adjusted vegetation index (SAVI) time series for the north-central sagebrush steppe portion of Desert Land & Livestock Ranch from 1972 to 1998. The best fit for the 3 management regimes and the entire time series are delineated. Missing years were replaced by linear interpolation.

strations of the protocol presented in this paper constitute an advance in the use of the technology. The advance consists of the context of an ecological framework based on states-and-transition models or catastrophe theory, the use of both retrospective monitoring and assessment of the response of vegetation and soil parameters, and the application to disturbance regimes from land management practices and climate change dynamics. It is an apparent rarity to have a time series of land management data to relate to changes in ecological indicators, but this combination is highly recommended where an understanding of causal mechanisms is required for informed decisions about land management practices. However, it should be realized that retrospective landscape-scale studies produce weaker inference than trajectory experiments because both controls and replicates are practically nonexistent in the former case (Hargrove and Pickering 1992).

Present research appears to focus primarily on emerging technologies. Some would consider Landsat MSS and TM data as old technology, yet an understanding of ecology realizes the influence of landscape legacies and thus the utility of historical archives of ecological data, including satellite data, for detecting this influence.

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