Chapter 13
Detection of Harbingers of Catastrophic Regime Shifts in Drylands

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Abstract Harbingers are early warnings of imminent ecosystem collapse and thus are aids to preventing land degradation. Dynamic systems are hypothesized to exhibit dampening or inflation of critical attributes at or near a threshold, which is a decreasing or increasing spatial or temporal trend, respectively. This behavior is diagnostic of a state change and can be operationalized as an early detection system. Consequently, we used a time series from 1972 to 1997 of seasonal soil-adjusted vegetation index (SAVI) data, a proxy for canopy cover that was derived from Landsat imagery of the Marine Corps Air Ground Combat Center. We used dynamical, trend, and autocorrelation function (ACF) time series analysis to find that the time series had an increasing linear trend that correlated with wet periods of the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO). High and low SAVI values were in wet and dry basins of attraction with a rapid shift from dry to wet period from 1981 to 1982. Mean SAVI dampening appears to have occurred 2–3 years prior to the shift. Consequently, this study suggests that this dampening trend of the mean SAVI can be used as a harbinger of land degradation.

Keywords Washington Allen—abrupt transition · Early warning · Imminent change · Remote sensing · Threshold · Time series

Introduction

The major dust storms that occurred during the US Dust Bowl era of the 1930s were hypothesized to be the result of the loss of vegetation cover at a critical point that led to bare-ground patches that were fragmented at local scales abruptly increasing in

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number, area, and connectivity to the regional scale of the western USA (Peters et al. 2004). This loss of vegetation cover and the resulting dust storms were attributed to multiyear severe droughts and land mismanagement that led to loss of agricultural livelihoods, the economic collapse of the agricultural sector, and the creation of the Soil Conservation Service, now the Natural Resources Conservation Service (NRCS) by the US Department of Agriculture. The NRCS was created to prevent this type of catastrophe from occurring again in rangelands and it would be advantageous to them and other land management agencies if changes in rangeland ecosystem attributes, e.g., vegetation cover, that lead to land degradation could be detected prior to a threshold being exceeded. This idea would require the early detection of harbingers or indicators of the imminent approach to a threshold (Brock and Carpenter 2006; Scheffer et al. 2009).

One such harbinger is the observed increase or decrease, also called negative and positive dampening, of the variability of measured community or ecosystem-level characteristics, e.g., vegetation cover or bare-ground patch dynamics, in time and space. This behavior harkens the change from one state to another or the approach to a threshold (Allen et al. 2005; Brock and Carpenter 2006; Wardwell and Allen 2009; Biggs et al. 2009; Scheffer et al. 2009). Time series analysis of autocorrelation in individual ecosystem characteristics can be used to detect harbingers that are represented as changes in key drivers and positive feedback interactions that are expressed as near shifts or breaks in scale (Briske et al. 2010). Ludwig et al. (2000) have shown that these large fluctuations in resource variability increase the success of random events to affect system reorganization. Consequently, the purpose of the study presented in this chapter is to determine whether the temporal behavior of a remotely sensed indicator of Dryland vegetation response, i.e., a vegetation index, under conditions of a known climatic regime shift can be used to retrospectively detect local-site behavior that are harbingers or early warning indicators of the pending approach of a threshold. A secondary purpose of this study is to detect the more and less ecologically resilient portions of Drylands that are subject to military training and testing activities. The US military installations occupy over 12 million ha of land, much of which is in Drylands, and hosts the largest population density of endangered species on federal lands (Benton et al. 2008). Consequently, this information would be helpful for directing military training exercises to the more productive areas of a landscape as well as directing ecological restoration practices to the most vulnerable. Consequently, this study will result in tools that will allow responsive land management from managers, stakeholders, and other decision makers (Scheffer et al. 2009).

Definitions

Drylands are areas where the ratio of the mean annual precipitation to the mean annual potential evapotranspiration ranges between 0 and 0.65. Drylands cover some 41 % of the terrestrial surface and provide ecosystem goods and services for 36 % of

the world's population (MEA 2005; Reynolds et al. 2007). However, the ecological condition and trend of Drylands at regional and global scales is unknown, primarily because they have demonstrated characteristics that are diagnostic of complex adaptive systems including emergent spatial patterns at the landscape scale (e.g., Rietkerk et al. 2004), multiple dynamic regimes or states in space and time (Archer 1989; Westoby et al. 1989; Lockwood and Lockwood 1993; Mayer and Rietkerk 2004), and nonlinear discontinuous or abrupt transitions at thresholds in space (e.g., ecotones) and time (Archer 1989; Scheffer et al. 2001).

There are a number of synonyms for thresholds including transition zones and tipping points (Washington-Allen et al. 2010). We define thresholds in the manner of Archer (1989), Westoby et al. (1989), Friedel (1991), and Scheffer et al. (2001) where a threshold is the abrupt transition from one state to another. Beisner et al. (2003) demonstrated that a state can be viewed from the community and/or the ecosystem levels of organization. For example, the US land management agencies used the concept of vegetation succession, specifically the compositional change in either plant functional types or physiognomic structure, e.g., the change of grassland to woodland, with respect to a reference state (usually the climax), as a way to monitor the ecological condition and trend of rangelands (Dyksterhuis 1949; Westoby et al. 1989; West 2003). This approach assumed linear and predictable vegetation dynamics, but actual observations demonstrated both discontinuous and continuous behavior in Dryland composition, spatial pattern, and biogeochemistry (Westoby et al. 1989; Stringham et al. 2003; Washington-Allen et al. 2008, 2009). Consequently, this community-level perspective has been expanded to include ecosystem science where changes in hydrological or biogeochemical parameters such as soil infiltration or nitrogen cycling are monitored and assessed in conjunction with vegetation compositional changes (Schlesinger et al. 1990; Stringham et al. 2003; Betlemeyer et al. 2004; Peterson et al. 2009).

Dryland degradation can be defined as a decrease in plant cover, density, productivity, or some other plant or vegetation parameter or measurement of attributes (Washington-Allen et al. 2004a, b; Washington-Allen et al. 2006). It is difficult to separate the relative contributions of climate, fire, and land management practices, particularly livestock grazing to changes in ecological indicators. Time series datasets of ecological indicators and drivers for 10 or more years, are required in order to replicate climatic drivers, such as the El Niño–Southern Oscillation (ENSO) that has a return interval of 3 to 7 years (Glantz 2001), in order to be able to separate climatic impacts from that of land management practices (Washington-Allen et al. 2006). The 40-year Landsat satellite image archive (1972 to the present), excluding Landsat 8, has pixel resolutions of 15 m in the panchromatic (black and white) and 30 m resolution for six of its multiple bands, and both 60 m and 120 m resolution for thermal bands. Ecological indicators that are diagnostic of vegetation parameters can be derived from the spectral and textural characteristics of historical imagery like Landsat (Tueller 1989; Quattrochi and Pelletier 1991; Washington-Allen et al. 2006). For example, the spectral characteristics of Landsat from blue to shortwave-infrared in detecting the reflectance of vegetation allows the development of biophysical models such as the Normalized Difference Vegetation Index (NDVI) (Rouse et al. 1973) that

Fig. 13.1 A true-color
Landsat image in the southern
Mojave Desert of the study
area: the Marine Corps Air
Ground Combat Center
(MCAGCC) in Twentynine
Palms, CA

relies on the difference in percent reflectance of incident near infrared (NIR) and red
(R) energy from leaf tissue. NDVI is calculated as:

$$NDVI = (NIR - R)/(NIR + R) \tag{13.1}$$

NDVI has been significantly correlated with vegetation attributes that are commonly
collected in the field including leaf area index (LAI), plant cover, phytomass, and net
primary productivity (Sellers 1985). A nearly 40-year time series of Landsat NDVI
can be characterized to look at possible state changes.

Methods

Study Area

The 238,645 ha Marine Corps Air Ground Combat Center (MCAGCC) was estab-
lished in 1952 and is a training facility that is located in the Mojave Desert, near
Twentynine Palms, California (Fig. 13.1; NRED 1999). MCAGCC is in the Great
Basin section of the Basin and Range physiographic province in mountain ranges,
hills, alluvial fans, drainages, playas, and lava flows. Elevations on the facility range
from 213 m to 1250 m above sea level. Soil textures range from gravelly fine sand to
gravelly very fine sand with indurated calcic horizons. The vegetation is sparse and is
comprised mainly of small shrubs and grasses of which the predominant plant species
are creosotebush (*Larrea tridentata*), burrobrush (*Coleogyne ramosissima*), cheese-
bush (*Hymenoclea salsola*), and catclaw acacia (*Acacia greggi*). In the more alkaline
areas of the Mojave-dominant species are allscale (*Atriplex polycarpa*), wingscale
(*Atriplex canescens*), and alkali blite (*Chenopodiium rubrum*). The most common

grass species is Indian ricegrass (*Oryzopsis hymenoides*). MCAGCC is habitat for the federally listed endangered species, desert tortoise *(Gopherus agassizii).* Land use at MCAGCC consists of live fire, combined arms, and maneuver training that simulates combat situations using ground infantry, tracked vehicles including tanks, and light-armored vehicles. There are also air-to-ground ordinance activities that result in localized impact zones (Natural Resources and Environmental Division (NRED) 1999).

Climatic Events

Temperature in the Mojave Desert ranges from $-13.3\,°C$ to $48.3\,°C$. The average precipitation from 1893 to 2001 was 137 mm year^{-1} with a range from 34 to 310 mm year^{-1} (Hereford et al. 2004). The dry season is May through September and the wet season is October through April (Hereford et al. 2004). Hereford et al. (2004, 2006) have shown that between 1893 and 2001, the Mojave experienced four major drought periods in 1893–1904, 1942–1975, 1988–1991, and 1999 (Breshears et al. 2005; Overpeck and Udall 2010) and two major wet (flood) periods in 1905, 1941, and 1976–1998. Hereford et al. (2004, 2006) using time series spectral analysis showed that these drought and flood events were reflections of both 35-year and 5-year periodicities that relate to the Pacific Decadal Oscillation (PDO), an index of the relative sea surface temperatures (SST) of the northern Pacific Ocean, and the ENSO, an atmosphere–ocean interaction that involves the warming of SST in the tropical Pacific Ocean from the equator to the southern coast of South America (El Niño) and the back-and-forth exchange of air masses between the eastern and western hemisphere at sub- and tropical latitudes (Southern Oscillation), respectively. Hereford et al. (2004, 2006) show that major climatic regime shifts in the Mojave were a function of the PDO cool phase (decreasing SST), that was manifest as the 1942–1975 drought, and PDO warm phase (increasing SST), that was manifest as the 1976–1998 wet period. The PDO warm phase also included the 1982–1985 very strong El Niño (Glantz 2001) and the 1988 La Niña drought called the "Great North American Drought" (Trenberth et al. 1988; Riebsame et al. 1991; Washington-Allen et al. 2009). La Niña is the cooling of SST in the tropical Pacific Ocean from the equator to the southern coast of South America, field studies of vegetation dynamics in the Mojave indicate that plant community composition changes with high mortality of plants during droughts and recruitment during wet periods of both annual and perennial grasses and woody plants (Beatley 1980; Webb et al. 2003; Hereford et al. 2006). The 1989–1991 drought period was particularly noteworthy for the high mortality of perennials (Webb et al. 2003), a phenomena which is currently being observed in the large die-offs of tree species in the drought–stricken southwestern USA (Breshears et al. 2005; Overpeck and Udall 2010). Additionally, Rundel and Gibson (1996) have shown that primary productivity in the Mojave increased under increased precipitation and of course decreased during droughts.

Data Acquisition

A time series of historical dry and wet season Landsat images from 1976 to 1996 (21 scenes) and 1972 to 1997 (20 scenes) were acquired of MCAGCC, respectively. The wet season dataset has a hiatus between the period 1972–1979 and is missing portion of scenes for the period 1973–1978. However, the existing dataset overlaps with the PDO cool phase from 1942 to 1975 and the warm phase from 1976 to 1998, as well as the previously mentioned very strong ENSO event of 1982–1985 (Glantz 2001). The dry season scenes were selected between May and June and the wet season scenes between October and November. For this study, six Landsat platforms with two different radiometers including Landsat Multispectral Scanner (MSS) and Thematic Mapper[TM] have been deployed. Because of the differing formats of 5- (Landsat MSS) and 8-bit[TM] and 30 m and 79 m pixel resolutions, images were: (1) rectified to a common map projection and resampled to a common resolution (60 m); (2) standardized by conversion to exoatmospheric reflectance values using Landsat postlaunch calibration gains and biases (e.g., Markham and Barker 1986); and (3) atmospherically corrected using a relative atmospheric correction procedure based on the use of pseudoinvariant features for multitemporal imagery (Jensen 2005; Washington-Allen et al. 2004a, b). The criteria for data acquisition were: low-cost acquisition of scenes that were representative of the dry and wet season, $\leq 10\%$ cloud cover, and anniversary dates between scenes. Path/Row location of scenes differed between platforms and in some years full scenes of the study area could not be acquired because the midline of the path/row grid passed through the study area, e.g., 1972–1981, 1983, 1985, 1986, 1989–1995 for the wet season imagery. However, at least 50 % of the study area was available for time series analysis. Table 13.1 lists the characteristics of the image data set.

Indicator Development

The effectiveness of NDVI for discriminating vegetation response is substantially reduced in drylands because of the sparser vegetation cover leading to increased sensitivity to soil background moisture and reflectance effects on the vegetation signal. Consequently the soil-adjusted vegetation index (SAVI) was developed from the NDVI to increase the vegetation signal relative to the soil noise (Huete 1988). SAVI is calculated as:

$$SAVI = [(NIR - R)/(NIR + R + L)] * (1 + L) \qquad (13.2)$$

The L is an adjustment factor which varies from 0–1 in accordance with soil background conditions (Huete 1988). The recommended L factor of 0.5 was used for all images (Huete 1988).

Table 13.1 The Landsat
satellite imagery dataset from
1972 to 1997 of the Marine
Corps Air Ground Combat
Center (MCAGCC) that was
used in this study

Acquisition Date	Landsat scanner and number	Season
10/02/1972	MSS 1	Wet
05/16/1976	MSS 2	Dry
06/16/1977	MSS 2	Dry
06/03/1978	MSS 2	Dry
10/28/1979	MSS 2	Wet
06/25/1979	MSS 2	Dry
10/23/1980	MSS 2	Wet
06/01/1980	MSS 2	Dry
11/05/1981	MSS 2	Wet
06/14/1981	MSS 2	Dry
12/12/1982	MSS 4	Wet
05/30/1982	MSS 3	Dry
11/13/1983	MSS 4	Wet
06/29/1983	MSS 4	Dry
11/30/1984	MSS 5	Wet
06/07/1984	MSS 5	Dry
11/1/1985	MSS 5	Wet
06/19/1985	MSS 5	Dry
11/13/1986	MSS 5	Wet
06/06/1986	MSS 5	Dry
11/16/1987	MSS 5	Wet
06/09/1987	MSS 5	Dry
10/24/1988	TM 5	Wet
06/02/1988	TM 5	Dry
10/20/1989	TM 5	Wet
06/05/1989	TM 5	Dry
10/30/1990	TM 5	Wet
06/08/1990	TM 5	Dry
11/11/1991	TM 5	Wet
06/04/1991	TM 5	Dry
10/28/1992	TM 5	Wet
06/14/1992	TM 5	Dry
11/07/1993	TM 5	Wet
06/16/1993	TM 5	Dry
11/19/1994	TM 5	Wet
06/19/1994	TM 5	Dry
10/05/1995	TM 5	Wet
05/30/1995	TM 5	Dry
11/08/1996	TM 5	Wet
06/08/1996	TM 5	Dry
10/26/1997	TM 5	Wet

Mean-Variance Plots

Graphical analysis of a dynamical system uses phase diagrams or portraits that de-
scribe the motion or trajectory of states through time (Morse et al. 2000). Pickup and
Foran (1987) developed a special case of this analysis called mean–variance analysis
(MVA) to characterize the spatiotemporal behavior of a remotely sensed vegetation
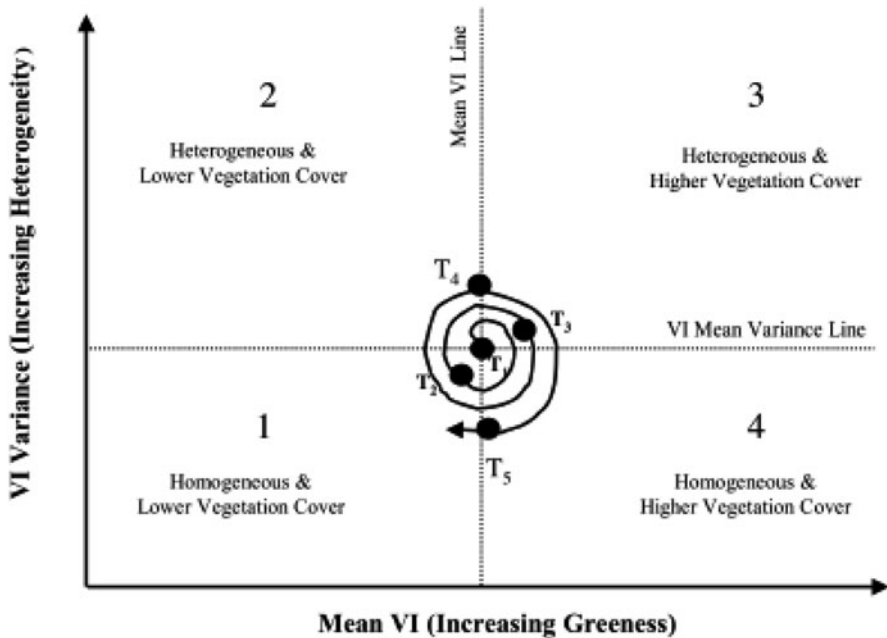index (VI). Washington-Allen et al. (2008) provide a conceptual model of a VI in

Fig. 13.2 A hypothetical statistical phase portrait of the interannual mean-variance dynamics of an agricultural landscape's vegetation index (VI). T = time. (Used with permission from *Ecology & Society*)

mean-variance space where the hypothetical trajectory of a VI of an agricultural crop that has been bred to minimize variability is described (Fig. 13.2). As previously discussed, the VI is a proxy for vegetation response, particularly percent canopy cover or biomass. Consequently, an NDVI value can be treated as percent canopy cover. The value of the VI variance represents the degree of landscape heterogeneity or balance between bare soil and vegetated patches (Pickup and Foran 1987). Thus, the variance and the mean together provide an indirect measure of a sites' susceptibility to soil erosion, where if a normal distribution is assumed, large VI variances indicate the likelihood that pixels with low VI values at the distribution's tails consist of either reduced vegetation or bare soil cover (Fig. 13.2).

The phase portrait is divided into four sectors or states that are delineated by the grand mean of the VI mean and the VI variance of a landscape's VI time series (Fig. 13.2). Each sector describes the state of a landscape's trajectory. For example, sector 1 (low mean and low variance) can be considered the most degraded state of this landscape, sector 2 (low mean and high variance) indicates that a higher proportion of the landscape tends towards bare ground and thus high susceptibility to erosion, sector 3 (high mean and high variance) means a higher proportion of the landscape has vegetation cover, but depending on skewness, a small proportion of the landscape is susceptible to erosion, and sector 4 (high mean and low variance) would be the most ideal and stable conditions for this VI landscape (Fig. 13.2). Mean-variance

plots were developed for whole landscape response as well as for each individual vegetation cover class. If the time series is long enough a mean-variance portrait can be used to delineate both seasonal and interannual dynamics of a landscape and discriminate regime shifts (Washington-Allen et al. 2008 and 2009).

Time Series Analysis

Characterization of the direction and strength of a trend can be accomplished with regression analysis (Yafee and McGhee 2000). A significant slope (ß) is a measure of the direction of trend, i.e., stable (0), increasing (+ ß) and decreasing (− ß), and the magnitude of the coefficient of determination (r^2) from a linear or polynomial regression measures the strength of the trend (Yafee and McGhee 2000). The autocorrelation function (ACF) can be used to detect thresholds in a vegetation index time series (Turchin and Ellner 2000; Washington-Allen et al. 2009). An abrupt and consistent sign change, i.e., (+) to (−) or vice versa and a significant ACF value usually indicate a threshold and allows delineation of the time series into different period states.

Results

SAVI Time Series

Figure 13.3 is the wet (1976–1996, a) and dry (1972–1997, b) season SAVI images of MCAGCC. During the wet season, the vegetation response (SAVI) tends to be from 0.05 to 0.44 throughout the period 1972–1997 (Fig. 13.3). However, during the dry season the SAVI value from 1976 to 1982 ranged from 0.06 to −0.35 and from 1983 to 1996, they ranged between 0.06 and −0.64. Trend analysis of the dry and wet season time series from 1972 to 1997 indicated a significant linear fit ($r^2 = 0.52$, $p < 0.05$) of increasing greenness from 1972 to 1997 (Fig. 13.4a). Examination of the ACF for this SAVI time series indicated an abrupt dampening of ACF values from lag 10 (0.10, 1981 compared to 1982) to lag 11 (0.28) to 15 (1981–1983 compared to 1982–1984) and a switch in ACF sign from (+) to (−) correlation at lag 16 (the dry season of 1985) (Fig. 13.4b). The trend of the SAVI variance from 1972 to 1997 was slightly increasing ($r^2 = 0.032$), but not significant.

Mean-Variance Plots

The wet season phase diagram indicated oscillating temporal dynamics that suggested one domain of attraction about the mean of the variance and the mean from 1972 to
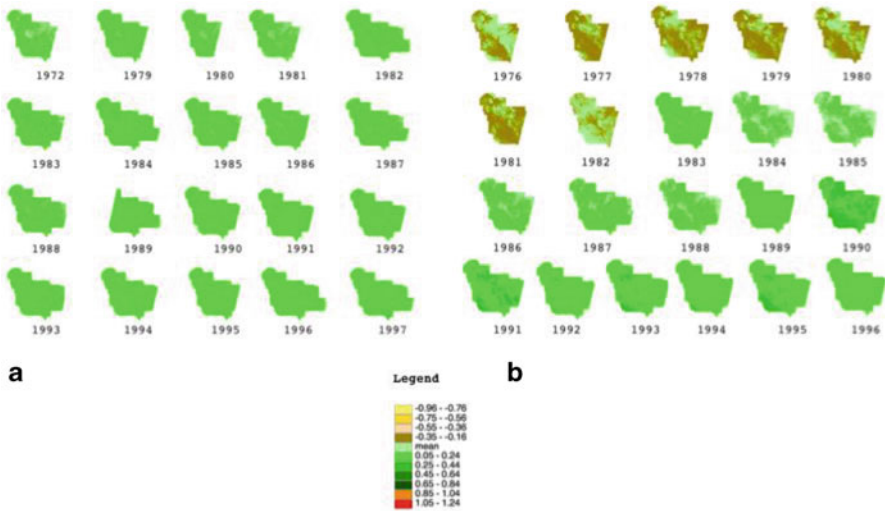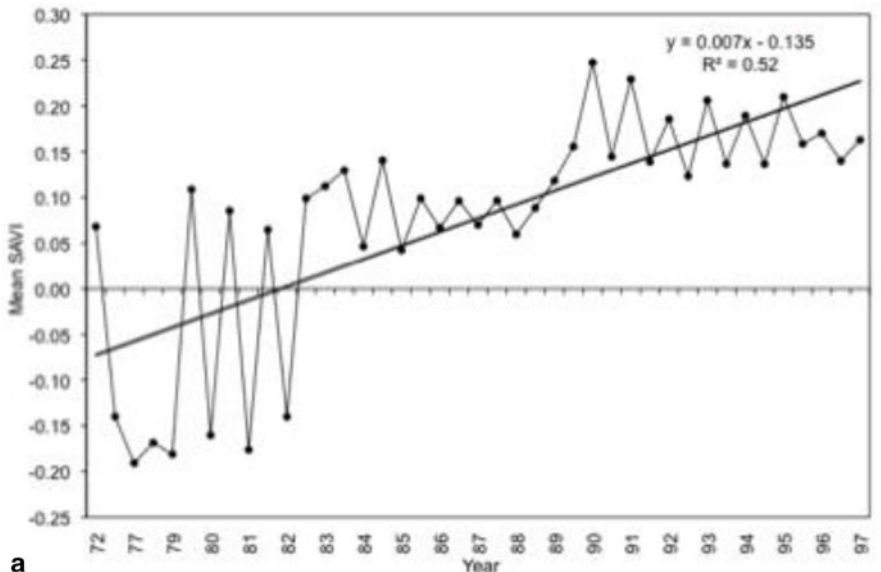
Fig. 13.3 a The wet (1972–1997) and **b** dry (1976–1996) season soil-adjusted vegetation index (SAVI) image time series of the Marine Corps Air Ground Combat Center (MCAGCC) in the southern Mojave Desert near Twentynine Palms, CA. The legend value range is ± 1 standard deviations between SAVI values from the mean

1997 (Fig. 13.5a). However, the dry season phase diagram indicated three domains of attraction: (1) from 1976 to 1982 of low SAVI and relatively higher variance, particularly 1980, than the other domains; (2) from 1983 to 1989 the orbit near the SAVI grand mean and variance; and (3) with relatively lower variance and higher mean SAVI from 1990 to 1997 (Fig. 13.5b). When the ACF was calculated on the dry season SAVI mean from 1976 to 1997 a switch in ACF sign from (+) to (−) correlation at lag 6 (1981 compared to 1982) to 7 (1982 compared to 1983) was detected (Fig. 13.6a). The trend in dry season SAVI mean ACF dampening was from lag 1 (1976 compared to 1977) to lag 6 (1981 compared to 1982) (Fig. 13.6a). When ACF was computed on the dry season SAVI variance from 1976 to 1996, a switch in ACF sign from (+) to (−) correlation at lag 6 (1981 compared to 1982) to 7 (1982 compared to 1983) was detected (Fig. 13.6b). The dry season SAVI ACF variance values from lag 3 to 6 decreased or dampened before the switch (Fig. 13.6b).

Discussion

The SAVI Landsat satellite time series was acquired at a time coincident with the major climatic regime shifts of the PDO and ENSO, specifically the 30-year (1942–1975) PDO cool phase drought and the 20-year (1976–1998) PDO warm phase wet period that included the very strong 1982–1985 El Niño wet period and the severe

a
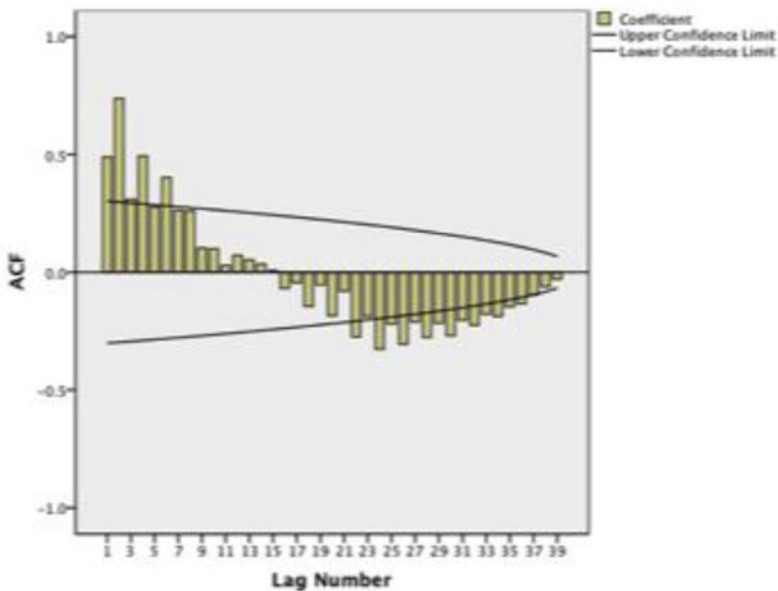
b

Fig. 13.4 Times series of the combined wet and dry season mean soil-adjusted vegetation index (SAVI) response for the Marine Corps Air Ground Combat Center (MCAGCC) from 1972 to 1997 (**a**). The linear fit suggests an increasing trend in greenness from 1972 to 1997. The autocorrelation function (ACF) of the combined time series (**b**) indicates significant changes during the dry season relative to the wet and that a regime shift had occurred between 1981 and 1982
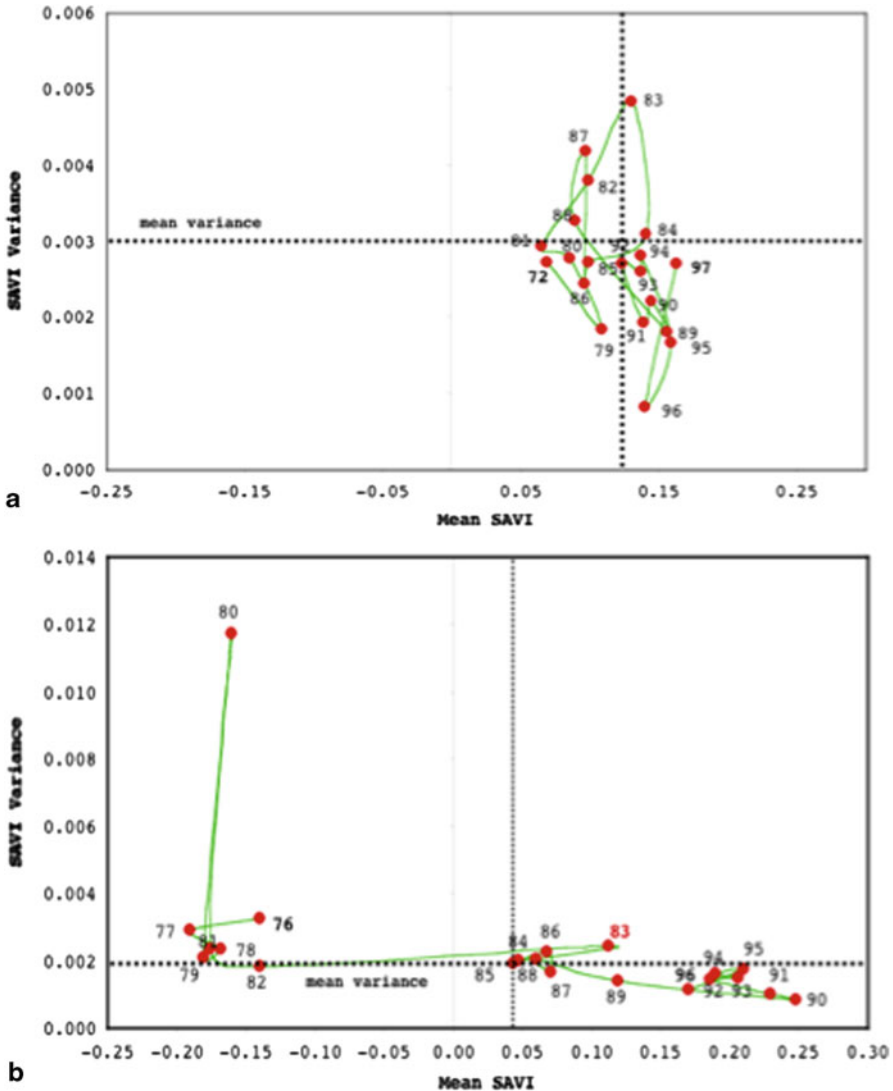
Fig. 13.5 Mean-Variance analysis of the dry (**a**) and wet (**b**) season soil-adjusted vegetation index (SAVI) scenes of the Marine Corps Air Ground Combat Center (MCAGCC) from 1972 to 1997. Three domains of attraction are evident during the dry season time series, whereas only one basin is evident during the wet season

droughts of the 1988–1991 La Niña. However, due to the data hiatus in the wet season imagery from 1973 to 1978, the PDO cool phase impact could not be detected.

The overall response of the Combat Center's SAVI response from 1972 to 1997 was an increasing linear trend that was buoyed by the PDO warm phase wet period and the increased wetness from the ENSO from 1982 to 1985 (Fig. 13.4). The
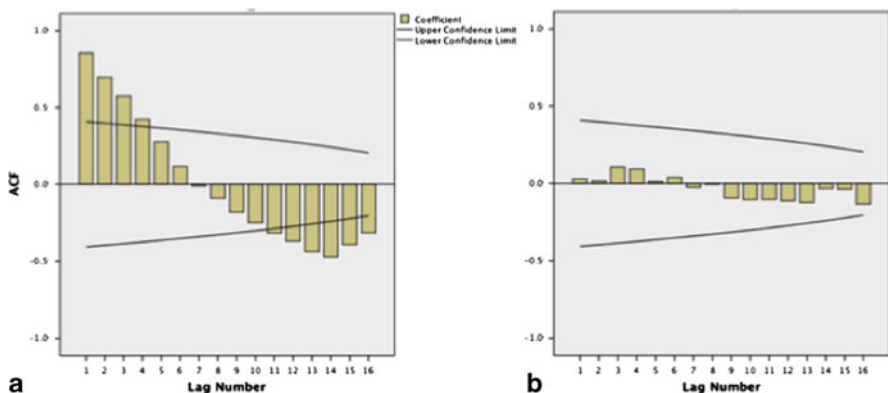
Fig. 13.6 The autocorrelation function (ACF) of the dry season mean soil-adjusted vegetation index (SAVI) (**a**) and the variance of SAVI (**b**) time series of the Marine Corps Air Ground Combat Center (MCAGCC) from 1976 to 1997

temporal response from 1972 to 1997 was bimodal with an abrupt shift occurring around 1981–1982 towards greater vegetation production. This regime shift was prominently detected by the dry season mean-variance and ACF analyses (Figs. 13.5 and 13.6) and coincided with the increased wetness of the southern Mojave with the inception of the El Niño wet period. The impacts of the droughts on vegetation were prominently detected in the SAVI image dry season time series from 1976 to 1981. It is likely that areas of high mortality were detected in this time sequence and could be further studied for persistence of drought impacts (Breshears et al. 2005; Washington-Allen et al. 2004a). This also applied to productive portions of the landscape and would be helpful for directing military training exercises to the more ecologically resilient portions of the Combat Center. This assessment of the response of the vegetation as measured by SAVI from 1972 to 1997, was consistent with the field vegetation and climate studies by Beatley (1980) and Hereford et al. (2006). In particular, the dry season response was more clearly indicative of vegetation response to climate than the wet season as evidenced by significant dry season ACF values in the overall time series (Fig. 13.4b). The dry season phase portrait indicated three domains of attraction for the southern Mojave with the wettest period of production during the years 1990–1996 (Fig. 13.5b). Consequently, Fig. 13.7 delineates the two major vegetation dynamic regimes: 1972–1981 and 1982–1997, of the vegetation response (SAVI) for the Combat Center.

Conclusions

A number of researchers have argued that either the dampening or increase of variance as a threshold approach may provide an early warning indicator or harbingers of change (Scheffer et al. 2009; Briske et al. 2010). However, though this behavior
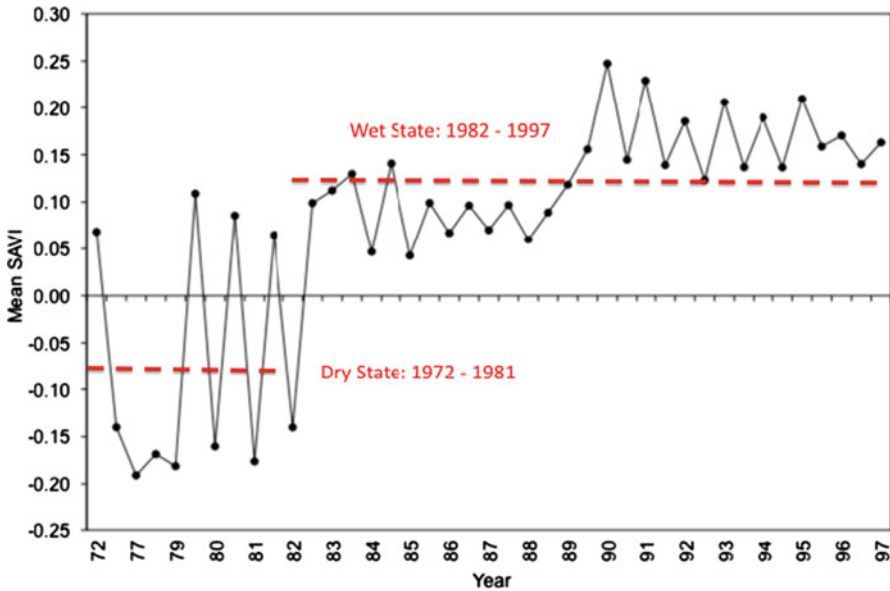
Fig. 13.7 The dry (1972–1981) and wet (1982–1997) dynamic regimes of the Marine Corps Air Ground Combat Center (MCAGCC) from 1972 to 1997

was observed for the SAVI variance, it was not significant in the overall time series nor for the dry season SAVI variance time series (Fig. 13.6b). We did find, however, that the ACF behavior of the SAVI mean dampened at a threshold, i.e., the ACF decreased from 1972 to 1981 and then changed sign from $(+)$ to $(-)$ ACF, and then increased incrementally after the threshold was crossed, peaking at lag 26 (1990) (Fig. 13.6a). In fact, the same dampening phenomenon is evident from 1990 in the entire time series and at lag 14 (1990) to 1997 of the dry season ACF (Fig. 13.6a). This dampening behavior suggests that a regime shift from the wet period of 1976–1998 to (observed) drought conditions may occur. Albeit a postmortem, the dampening of the ACF function from 1990 was a harbinger of the 1999–2003 droughts in the Mojave (Hereford et al. 2006) and the present droughts from 1999 to 2009 in the southwestern USA (Overpeck and Udall 2010). Consequently, the dampening of the ACF after a peak may be a harbinger of a dynamic regime shift induced by ENSO and the ACF sign change from $(-)$ to $(+)$ ACF or vice versa is indicative of a threshold. For MCAGCC this provided an early warning for drought mitigation techniques, as they go from a wet cycle to a dry, and implementation of ecological restoration techniques, as they take advantage of the water subsidies provided by an El Niño wet period (Holmgren and Scheffer 2001; Holmgren et al. 2001).

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