

Response of an aridland ecosystem to interannual climate variability and prolonged drought

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Abstract Water is a key driver of ecosystem processes in aridland ecosystems. Thus, changes in climate could have significant impacts on ecosystem structure and function. In the southwestern US, interactions among regional climate drivers (e.g., El Niño Southern Oscillation) and topographically controlled convective storms create a spatially and temporally variable precipitation regime that governs the rate and magnitude of ecosystem processes. We quantified the spatial and temporal distribution of reduced grassland greenness in response to seasonal and annual variation in precipitation at two scales at the Sevilleta Long Term Ecological Research site in central New Mexico, using Normalized Difference Vegetation Index (NDVI) values from bi-weekly AVHRR data and seasonal ETM data from 1989 to 2005. We used spatially explicit NDVI Z-scores to identify times and places of significantly reduced greenness and related those to interactions between plant functional type, seasonal climate variation, and topography. Seasonal greenness was bimodal with a small peak in spring and a stronger peak following the summer monsoon. Greenness was generally spatially homogeneous in spring and more spatially

variable in summer. From 2001 through spring 2002, drought effects were evidenced by a 4-fold increase in the number of pixels showing significantly low greenness. Spatial distribution of low greenness was initially modulated by topographic position, but as the drought intensified spread throughout the study area. Vegetation green up occurred rapidly when drought conditions ceased. We conclude that drought effects vary spatially over time, pervasive drought reduces broad-scale spatial heterogeneity, and greenness patterns recover rapidly when drought conditions end.

Keywords Aridland ecosystems · Drought · Grasslands · New Mexico · NDVI

Introduction

Local and regional climate drivers strongly affect the distribution and composition of ecosystems worldwide. Indeed, potential evapotranspiration, an integrative measure of radiation and temperature, is frequently correlated with measures of ecosystem structure and function (Rosenzweig 1968; Meentemeyer 1978; Frank and Inouye 1994). Global change models predict that climate variability and extreme events are likely to increase in response to elevated concentrations of atmospheric CO₂ (Easterling et al. 2000; IPCC 2001). Climate variability has been implicated in

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the transition from grass- to shrub-dominated ecosystems in many arid regions (Giannini et al. 2003; Kerr 2003; Weldeab et al. 2005; Williams and Albertson 2006). Determining the degree to which increased climate variability will affect ecosystem processes requires long-term analysis of ecosystem response to past and current climate variability and climate extremes. Such understanding is essential to predict the future consequences of increased climate variability on ecosystem structure and function.

In the southwestern US, highly non-linear interactions among the Pacific Decadal Oscillation (PDO), the El Niño Southern Oscillation (ENSO), the annual summer monsoon and topographically controlled convective storms create a spatially and temporally variable regional climate (White et al. 2005). Ecosystem processes in arid landscapes, such as net primary production, vary accordingly in response to these precipitation-driven “hot spots” and “hot moments” (McClain et al. 2003), which has important implications for community dynamics and trophic interactions (Friggens 2003; Baez et al. 2006). Since 1998 the southwestern US has experienced pervasive drought which has caused rapid landscape change, including shrub encroachment (Van Auken 2000), widespread tree mortality (Ogle et al. 2000; Breshears et al. 2005; Romme et al. 2006), increased probability of wildfires (Carter 2003; Lenart 2004b), and intensified regional water shortages (Lenart 2004a). Thus, changes in seasonal and annual rainfall patterns influenced by large-scale climate drivers have dramatically and rapidly altered structure and function in aridland ecosystems. Extensive drought has the potential to cause rapid and persistent landscape change (Allen and Breshears 1998) that, coupled with anthropogenic impacts (e.g., N deposition), could have substantial implications for the ecosystem.

All ecosystems persist within some range of climate variability (Huxman et al. 2004). Grass- and shrub-dominated ecosystems in the southwestern US experience high interannual variation in precipitation and periodic extreme climatic events, especially prolonged droughts (Borchert 1950; Sheppard et al. 2002). Aboveground net primary production in grasslands exhibits greater

sensitivity to interannual climate fluctuations than other ecosystem types in North America (Knapp and Smith 2001). Moreover, under drought conditions, maximum ecosystem rain use efficiency in deserts, grasslands, and forests converge on values typical of aridland ecosystems (Huxman et al. 2004). As a consequence, aridland ecosystems may show high temporal sensitivity to climate variation as well as high resilience following extreme climatic events. Given that water is the key limiting resource in arid ecosystems (Noy-Meir 1973; Schwinning and Sala 2004), we hypothesize that short-term, low severity interannual climate fluctuations will result in large changes in grassland productivity from year to year, but that grassland production will recover rapidly when drought conditions end.

In this paper, we used a 17-year time series of satellite data to quantify, at the landscape scale, the response of desert grass- and shrub-dominated communities to interannual climate variability and pervasive drought. Specifically, we used the Normalized Difference Vegetation Index (NDVI) as a surrogate for vegetation productivity and measured (1) interannual fluctuations in NDVI by season in response to precipitation variability, and (2) spatio-temporal patterns of low NDVI in relation to interactions between drought conditions and the heterogeneous landscape, at two spatial scales. We used these spatio-temporal patterns to infer linkages between multiple processes and responses in this aridland ecosystem due to rainfall and drought.

Methods

Study area

Our study was conducted at the Sevilleta Long Term Ecological Research (LTER) site located in and around the Sevilleta National Wildlife Refuge (SNWR) in central New Mexico, USA (Fig. 1). The SNWR is bisected by the Rio Grande and occurs at the ecotone between three major grassland biomes, two of which are the focus of this study: Great Plains grassland to the north, and Chihuahuan Desert grassland and shrubland to the south (Fig. 1a). Our focal landscape was a

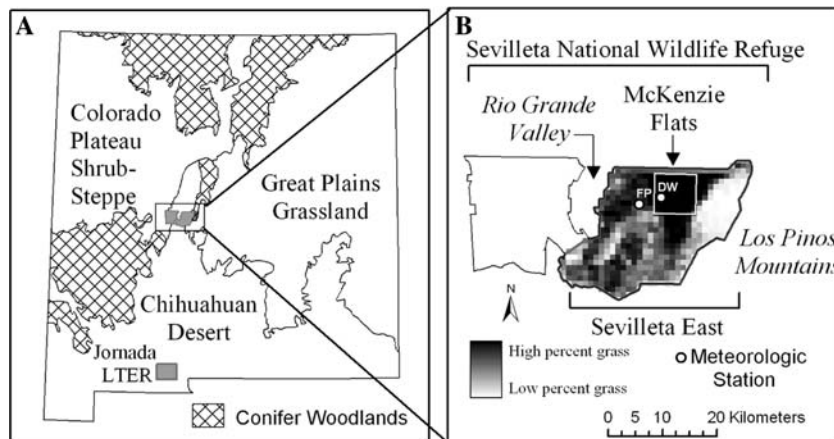


Fig. 1 (A) Location of the Sevilleta National Wildlife Refuge (SNWR) in central New Mexico at the transition between Central Plains grassland and Chihuahuan Desert grassland and shrubland vegetation. (B) Grass- and shrub-dominated vegetation in the eastern portion of the study area, with the Rio Grande riparian forest to the west and

piñon-juniper woodlands in the Los Piños Mountains to the east. Percent grass at 1-km resolution was calculated from a 30-m resolution vegetation map. McKenzie Flats is an area of desert grassland into which native creosotebush is invading from the south

64,000 ha area on the east half of the refuge, extending from the low elevation riparian forest dominated by *Populus fremontii* east to the base of the Los Piños Mountains (Fig. 1b). The study area was subdivided into northern and southern zones roughly corresponding to the ecotone between the Great Plains and Chihuahuan Desert biomes. The northern zone contains an intensively studied grassland area, McKenzie Flats, which consists of a mixture of long-lived C_4 grasses from both biomes (e.g., *Bouteloua gracilis*, *B. eriopoda*, *Muhlenbergia arenicola*, *Hilaria jamesii* and *Sporobolus* spp). The southern zone contains primarily Chihuahuan Desert shrubland dominated by creosotebush (*Larrea tridentata*) and irregularly distributed patches of *B. eriopoda* grassland (Hochstrasser et al. 2002). McKenzie Flats, within the northern zone, was the focus of our more detailed analyses within the larger eastern portion of the study area.

Climatic variables

Lower elevations in the SNWR receive an average of 255 mm precipitation per year of which 60% occurs during the summer monsoon from July through September and the remainder primarily from winter frontal systems (Gosz et al. 1995). The relative contribution of summer

monsoon and winter rains varies considerably from one year to the next. Based on meteorological data from the Sevilleta LTER (<http://www.sev.lter.net.edu/>), the lower elevations in this region are in moisture deficit most of the year, with potential surpluses only during August, December, and January. Mean annual temperature from 1989 to 2005 at the Deep Well meteorological station (Fig. 1b) on McKenzie Flats was 13.2°C, with a January low of 1.6°C and a July high of 25.1°C.

Local precipitation was measured throughout the study period at two weather stations on McKenzie Flats (Deep Well and Five Points, Fig. 1b). We used the Palmer Drought Severity Index (PDSI; Palmer 1965) for New Mexico Division 5 (<http://www1.ncdc.noaa.gov/pub/data/cirs/>) to quantify drought conditions. PDSI is an integrative measure of both precipitation and soil moisture and reflects long-term conditions.

Vegetation variables

Aboveground net primary production (ANPP), a key process that integrates ecosystem structure and function, has been shown to vary in response to climate in many ecosystems; yet the relative importance of particular climate variables changes among ecosystems (McNaughton et al.

1989; Knapp and Smith 2001). Given the extensive area of observation necessary to understand spatial variability in productivity related to drought, we used satellite-derived Normalized Difference Vegetation Index (NDVI, Tucker 1979) “greenness” as a surrogate for productivity (Justice et al. 1985; Sellers 1985; Prince 1991; Myneni et al. 1997; Chen et al. 2001; Moody and Johnson 2001; Tucker et al. 2001; Shabanov et al. 2002; Lu et al. 2003). NDVI has been shown to effectively measure absorbed photosynthetically active radiation, which is directly and linearly related to carbon flux through an ecosystem (Sellers et al. 1992; Law and Waring 1994). For example, Paruelo and Lauenroth (1995) and Jobbagy et al. (2002) found a positive correlation between NDVI and mean annual precipitation across rainfall gradients in grasslands of North and South America. Although the Soil-Adjusted NDVI (SAVI) has been shown to be a better surrogate for productivity in some arid systems (Huete 1988), NDVI has been shown to be more highly correlated with productivity than SAVI at the SNWR (Shore 2000, unpublished data).

At SNWR, ground-based measures of productivity are available for two sites near the Five Points meteorological station (Fig. 1b) where non-destructive measurements of productivity began in 1999 (for methods see Huenneke et al. 2001). The measurements incorporate all above-ground living biomass, both green and woody. We found a weak but significant positive correlation between 30-m resolution Enhanced Thematic Mapper (ETM) satellite-derived NDVI values and ground-based productivity measures at the SNWR ($R^2 = 0.29$, $N = 320$). The relationship is stronger for grasses ($R^2 = 0.42$) than for shrubs ($R^2 = 0.10$), reflecting the high percentage of woody biomass in shrubs, non-detectable by NDVI. To some extent, the relationship is weakened by differences in sampling scale (1-m² vs. 30-m² grain size). Nevertheless, changes in NDVI values do co-vary with changes in productivity at our study site.

Since productivity is related to NDVI and climate is related to productivity, we would expect a relationship between climate and NDVI, and that NDVI can successfully be used to monitor vegetation response to drought. (Di

et al. 1994; Myneni et al. 1997; Richard and Pocard 1998; Kawabata et al. 2001; Potter and Brooks 2001; Foody 2003; Ji and Peters 2003; Potter et al. 2003; Dunham et al. 2005). Indeed, Weiss et al. (2004) demonstrated that NDVI values near six weather stations located on the SNWR were correlated with key climate variables, including temperature, precipitation and wind speed.

Variation in NDVI was assessed at two scales. We analyzed NDVI values from Advanced Very High Resolution Radiometer (AVHRR) data from 1989 to 2005 for the eastern portion of the SNWR (broader scale) and ETM data from 1989 to 2003 for McKenzie Flats (local scale) using both average and spatially explicit values. AVHRR measurements are 14-day composites (Appendix 1; 26 periods per year) at 1-km resolution. Composites record the maximum NDVI value measured for a given pixel over the 14-day period. The AVHRR images used atmospheric correction algorithms developed by the USGS in 2001 and applied retrospectively to earlier NDVI values (<http://www.edc.usgs.gov/greenness/whatnew.html>) to generate a consistent time series across measurements made by different AVHRR sensors. We calculated average AVHRR NDVI values by period and, based on those results, grouped the 26 AVHRR periods into three seasons: spring/summer, summer/fall and winter (Appendix 1).

For the fine-scale analyses, we used two ETM scenes per year (Appendix 1; spring/early summer and late summer/fall seasons) at 30-m resolution. Scenes were radiometrically calibrated for sun angle and atmospheric conditions. For analyses at both scales, we used a 30-m vegetation map of the SNWR (Muldavin et al. 1998) to mask out piñon-juniper woodland areas in the Los Piños Mountains on the eastern portion of the study area and the riparian corridor to the west. The 30-m vegetation map was then used to estimate the percent cover of grasses for each remaining 1-km AVHRR pixel (Fig. 1B). The McKenzie Flats study area was limited to a square area consisting of greater than 90% grass cover. Burned areas on McKenzie Flats in 1995, 2001 and 2003 were masked in the periods immediately following the fires.

Data analyses

We calculated mean NDVI values for each AVHRR and ETM image:

$$\overline{\text{NDVI}}_{kl} = \left(\sum_{i=1, j=1}^{N, M} \text{NDVI}_{ij} \right) / N * M$$

for pixels in N rows (i) and M columns (j) in period (k) and year (l), and plotted them in consecutive order. Mean AVHRR NDVI values deviating more than 0.05 from values for both the previous and following period were considered to be statistical outliers and removed from the analysis. Although these values could reflect actual period to period variation in NDVI as a function of climate variation, the likelihood of such large changes in greenness over such a broad area lasting less than 2 weeks is small.

Residual NDVI for a given image in period or season (k) and year (l) (αNDVI_{kl}) is the difference between mean NDVI for that image (NDVI_{kl}) and mean NDVI for all images from that period (NDVI_k):

$$\alpha\text{NDVI}_{kl} = \overline{\text{NDVI}}_{kl} - \overline{\text{NDVI}}_k.$$

We used spatially explicit Z -scores to identify significantly low NDVI values for each pixel, comparing its NDVI value with the distribution of values for that pixel in the same period in other years (Peters et al. 2002). Since Z -scores are a parametric statistic, we took random samples and tested for normality of data from all spring and fall periods using Shapiro–Wilks W test. Normality was found for 96% of spring samples and 86% of fall samples (342 samples per season, $N = 14$ for each sample, threshold $P = 0.05$). The Z -score for a given pixel (ij) for a specific period or season (k), for all years, was calculated as:

$$Z_{ijkl} = \frac{\text{NDVI}_{ijkl} - \overline{\text{NDVI}}_{ijk}}{\sigma\text{NDVI}_{ijk}}.$$

Z -scores less than -1.96 represent pixels with significantly low NDVI values, having less than 5% probability of random occurrence compared with the historical distribution of values for that

pixel. This approach is conceptually similar to data quality algorithms designed to identify statistically significant “outliers” in spatially coherent time series data (L. Larkey et al. submitted, Collins et al. in press).

Results

NDVI-based greenness values vary seasonally and spatially across the study area (Fig. 2). We found a bimodal pattern of greenness with a moderate peak in spring following winter rains and a much strong peak in late summer in response to monsoon precipitation (Fig. 2a). Spatially explicit average NDVI values show that the relatively low spring greenness values are widely distributed across the landscape (Fig. 2b). In contrast, late summer greenness values are spatially variable concentrated primarily in the grass-dominated vegetation in the northeastern portion of the study area (Fig. 2b). Thus, seasonal greenness patterns reflect seasonal patterns in annual precipitation, but peak greenness varies spatially in response to local distribution of rainfall and dominance by C_4 grasses.

NDVI values from AVHRR imagery consistently overestimated productivity relative to ETM images (Fig. 3a, b). Overestimation was more severe for fall ETM images (Fig. 3b). To compensate for differences between sensors, we converted raw NDVI values to residual values (Fig. 3c) allowing comparison between image types and seasons. Residual NDVI values indicate an interval of sustained higher than normal greenness from 1996 through mid-2000 followed by lower than normal NDVI values until mid-2003 following 2 years of low summer rainfall (Fig. 4). Monthly precipitation averaged 22% higher from 1997 through early 2000 compared with monthly amounts from 2000 through mid-2003 (Fig. 4).

Drought effects are evident in the AVHRR data over more than 20% of the landscape in 1989, 1990, 1994, and throughout the interval from 2000 through 2004 (Fig. 5a). Widespread drought occurred from April 2001 through August 2002 and briefly again in spring of 2003

Fig. 2 (A) Mean AVHRR NDVI values by sampling period showing bimodal distribution of greenness during the growing season. (B) Spatially explicit mean AVHRR NDVI values from 1989 to 2005 for spring and late summer/fall seasons showing higher greenness in the late summer/fall season and in the northeastern portion of the study area

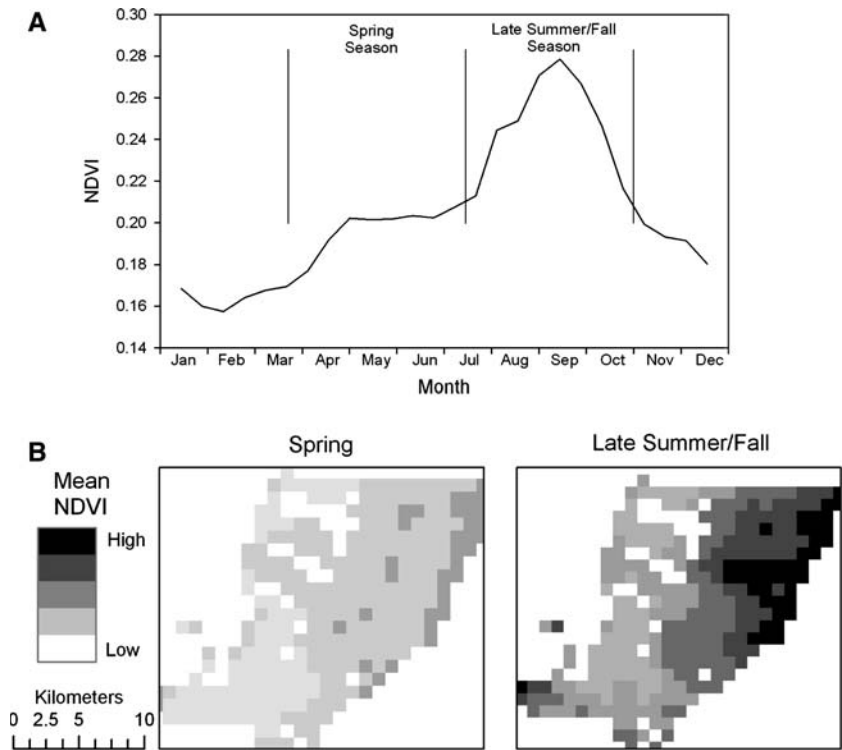
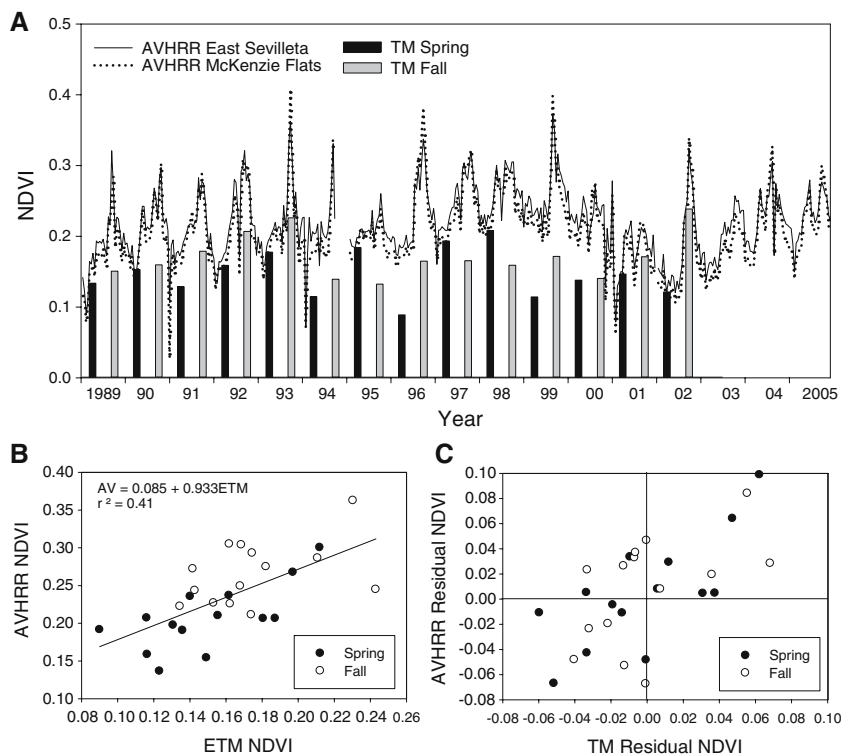


Fig. 3 Comparison of NDVI values from ETM (30 m resolution) and AVHRR (1 km resolution) images. (A) Temporal patterns of unconverted NDVI values, showing seasonal effects and overestimation of NDVI by AVHRR relative to ETM. (B) Unconverted NDVI values from samples, showing seasonal effects and quantifying the overestimation of NDVI by AVHRR imagery. (C) Residual NDVI values correcting for bias in AVHRR data



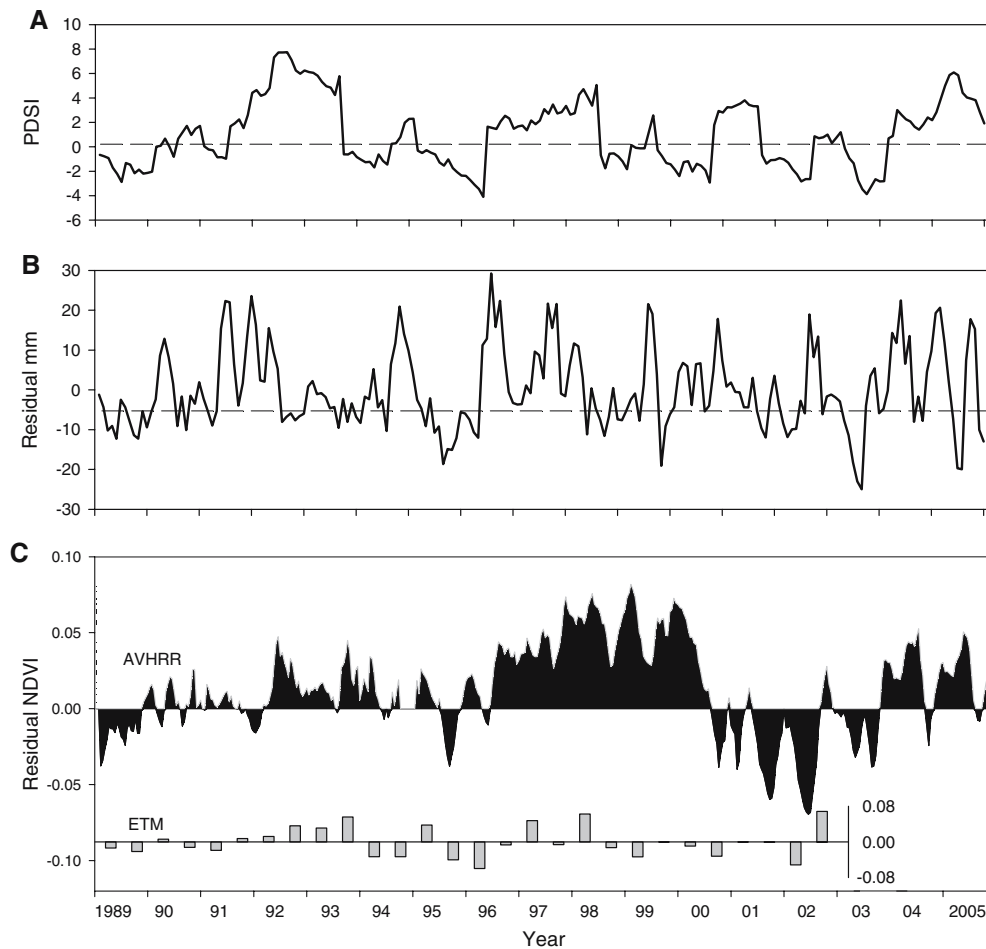


Fig. 4 Precipitation, drought, and vegetation response indicators. **(A)** Palmer Drought Severity Index, **(B)** Local precipitation at the Deep Well meteorological station, and

(C) Temporal patterns of residual NDVI from ETM and AVHRR data

(Fig. 5a). Drought effects were stronger in the southern versus northern parts of the study area (Fig. 5b). A spatially explicit analysis of drought response from 2001 through 2002 showed that drought effects were scattered throughout the region in April 2001, but were widespread by early June 2001 and remained so through August 2002 (Fig. 5b). Widespread drought effects disappeared after a large precipitation event in September 2002, showing the capacity of these aridland ecosystems to recover rapidly from prolonged drought.

High spatial resolution ETM imagery provide a more detailed understanding of drought effects

in the grass-dominated northeastern portion of the study area (Fig. 6) compared to the coarser resolution AVHRR data. At McKenzie Flats, significantly low greenness values were uncommon in summer of 2000 (<1% of the landscape at the 0.05 significance level; 12% of the landscape at the 0.10 significance level) and absent in the scenes for 2001 and 2002. The Deep Well precipitation record indicates that extremely low precipitation (less than 50% of average) at McKenzie Flats occurred only sporadically in 2001 and 2002 (Table 1), and that ETM images were selected during or shortly after those months (Appendix 1). In both years there were

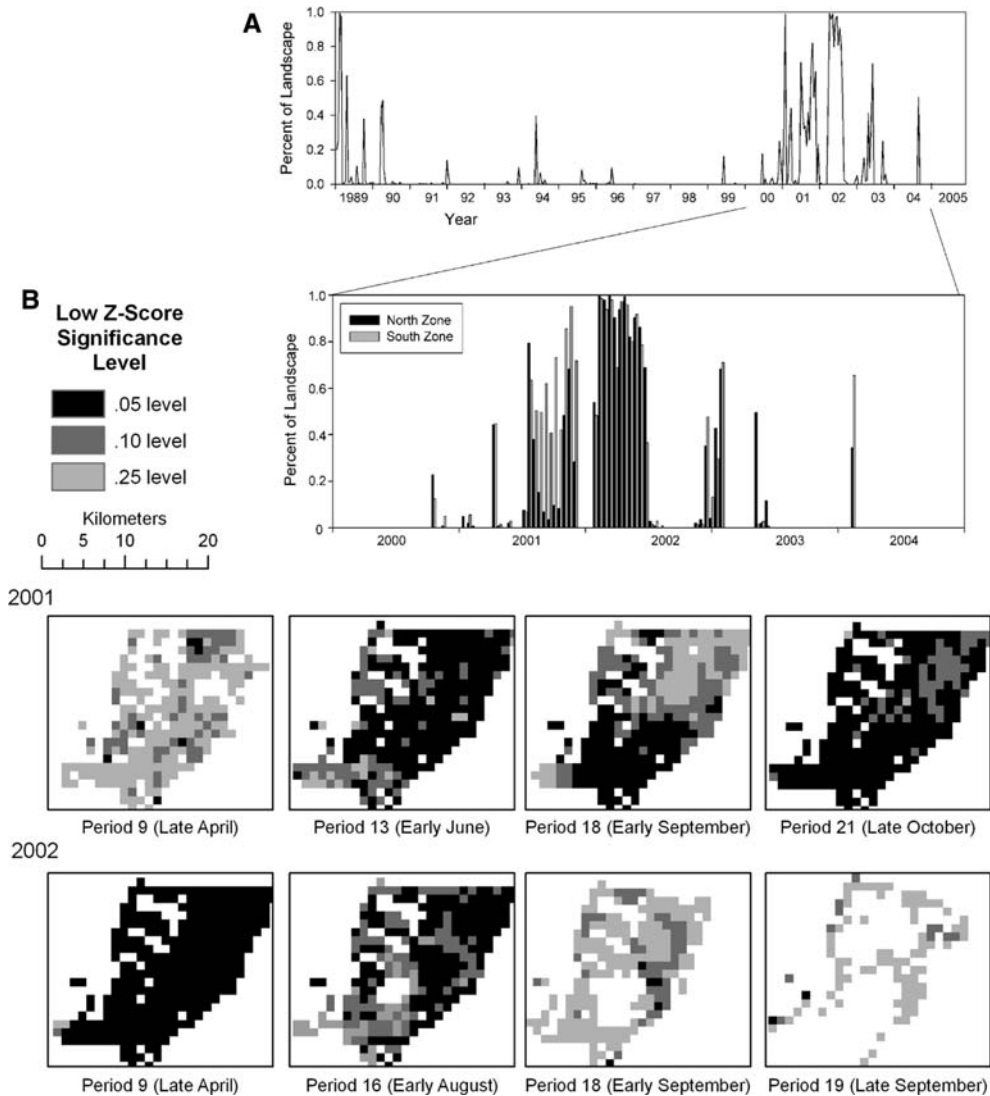


Fig. 5 (A) Times series from 1989 to 2005, showing proportion of landscape with significantly low NDVI values (AVHRR Z-scores $P \leq 0.05$). The drought period from 2000 to 2004 is expanded to show proportions from northern and southern halves of the study area. (B)

Response of vegetation greenness (NDVI) during the drought period from April 2001 to September 2002. Note rapid vegetation recovery following precipitation in September 2002

months during the productive seasons with closer to normal precipitation. The NDVI residual analysis (Fig. 4c) is also consistent with this interpretation, showing that the spring 2002 image does in fact have an average NDVI value that is much lower than the long-term mean, even if it does not show pixels with significantly low NDVI. Both 2002 images show considerable NDVI variability that is spatially relatively

homogenous in the spring and heterogeneous during the fall.

Discussion

Although climatic variability and extreme climatic events characterize desert ecosystems, the effects of seasonal and annual climate patterns on

Fig. 6 Spatially explicit mean ETM NDVI values from 2000 to 2002 for spring and late summer/fall seasons on McKenzie Flats showing the small number of significantly low NDVI values (Z-scores $P \leq 0.05$) in grassland vegetation during this period

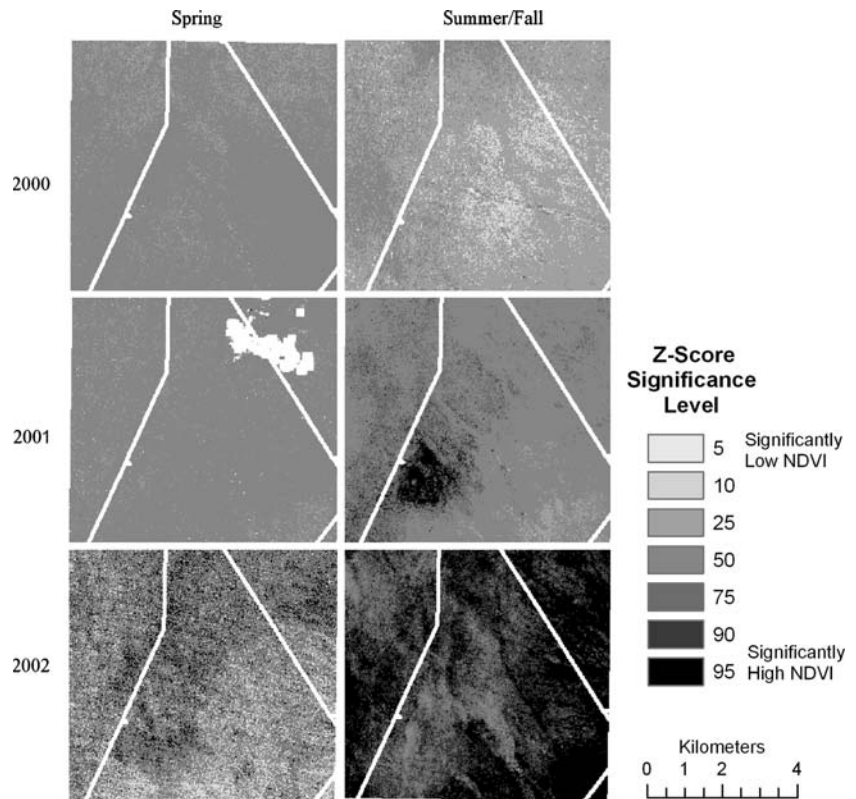


Table 1 Selected precipitation amounts at the Deep Well meteorological station at McKenzie Flats as a percentage of 1989–2005 mean precipitation

	1995	1996	2000	2001	2002
Jan	0.89	0.73	0	1.31	0.38
Feb	1.47	0.33	0.13	0.63	0.49
Mar	0.31	0.11	2.86	1.41	0
Apr	0.37	0	0.89	0.60	0.09
May	0.13	0	0	0.64	0.68
June	0.15	0.37	0.10	0.08	0.02
July	0.14	0.82	1.76	0.89	1.27
August	0.90	1.87	0.78	1.42	0.71
September	0.50	1.42	0.02	0.18	2.61
October	0.06	1.56	2.46	0.24	0.07
November	0.61	0.89	2.25	1.89	1.20
December	0.28	0	1.24	0.94	1.03

Shaded cells indicate months when precipitation was less than 50% of the 1989–2005 average

spatial variability of productivity in these ecosystems have rarely been quantified. We found that for desert grass- and shrub-dominated vegetation

in central New Mexico (1) landscape-scale drought effects varied seasonally and spatially from one year to the next, (2) pervasive drought reduced large-scale spatial heterogeneity in aboveground greenness (NDVI), and (3) greenness recovered rapidly when drought conditions ended. These results demonstrate both the high degree of spatial and temporal coupling between variation in rainfall patterns and ecosystem processes and the resilience of aridland ecosystems to short-term climatic fluctuations.

The landscape-scale patterns of drought effects and recovery resulted from a combination of factors, including spatial differences in local precipitation events, year-to-year differences in amount of winter vs. summer precipitation, and differences in functional types among dominant species (Reynolds et al. 2004). The north–south transition represents the ecotone between the C_4 -dominated grassland in the north and C_3 -dominated shrubland to the south. Physiological differences in functional types of dominant

species could be responsible, in part, for the observed landscape-scale patterns in overall productivity and drought response. Peak production of creosotebush, a C_3 shrub, occurred in late spring as a function of winter and spring rainfall, whereas production in the C_4 -dominated grassland was more dependent on summer rains, consistent with findings elsewhere in Chihuahuan desert ecosystems (Huenneke et al. 2002). Thus, differences in productivity response between northern and southern areas may result from distinct functional type responses to differences in the amount of seasonal rather than annual patterns in rainfall.

Total precipitation was also higher in the northern compared to the southern half of the study area and may explain the small number of significantly low ETM NDVI values on McKenzie Flats during the 2001–2002 drought period. The northeastern grasslands experienced orographic rescue from drought through an increase in the number and intensity of topographically controlled convective storms particularly during the summer monsoon (Gosz et al. 1995). Increased precipitation from these events, along with runoff from adjacent areas during storm events, may increase water availability locally (Ludwig et al. 2005), creating a topographically induced refugium from drought. Drought effects at McKenzie Flats were observed in 1995–1996 when low summer precipitation followed low winter precipitation. During the summer months residual NDVI values were strongly correlated with number of monsoon days ($\rho = 0.430$, $N = 39$, $P = 0.007$). Thus, orographic rescue increases precipitation locally except during extended rain-free periods.

In central New Mexico, two seasonal climatic forces, winter frontal systems and summer monsoons, each of which is controlled by distinct large-scale climate drivers, interact to create seasonal and annual differences in the size, frequency, intensity, and duration of precipitation (Gutzler et al. 2002). Winter and spring precipitation events are relatively uniformly distributed spatially, reflecting the dominant ENSO frontal systems that are primarily responsible for winter

and spring precipitation across southwestern North America. These ENSO-driven, spatially homogeneous precipitation events may last for days replenishing shallow and deep soil moisture and generating a more or less uniform springtime pattern of productivity by C_3 plants over relatively broad areas (Loik et al. 2004). Drought effects related to low winter and spring precipitation would also be widespread and uniformly distributed, as well. Together, these patterns explain the relatively homogeneous spatial distribution of early season productivity at the SNWR from 1 year to the next.

In contrast, summer rainfall patterns are patchy in space and time, reflecting the nature of summer monsoonal precipitation. Monsoon rains may be locally intense over a limited spatial extent. Such events occur when evapotranspiration rates are high, thus the effects of each precipitation event on plant production may be transient (Huxman et al. 2004; Belnap et al. 2006). As noted above, summer weather events interact with topography generating higher precipitation near the mountains (Gosz et al. 1995). Nevertheless, at the local scale, within-season precipitation events remain unpredictable and may fall at any particular location, increasing within- and between-season spatial patchiness in productivity.

Differences between AVHRR and ETM NDVI may most likely be attributed to an interaction between vegetation characteristics in semi-arid grasslands and AVHRR compositing methods. Interpretation of NDVI in sparse vegetation is problematic for multiple reasons (Moran et al. 1997; Richard and Pocard 1998; Leprieur et al. 2000; Ji and Peters 2003; Fensholt et al. 2004; Detar et al. 2006). In this case, interpretation is complicated by the rapid response of semi-arid vegetation to changes in water availability, which results in patchy greenness in space and time. On any given day, there is likely to be a percentage of the landscape that is green, but the location of greenness can change over the course of several days. Daily data from AVHRR capture the location of greenness on each day. These are converted to 14-day compos-

ites that record the maximum NDVI value for each pixel during that period. The composite captures all green patches throughout the 14-day period and accumulates them into a single scene, resulting in an overestimation of greenness in comparison with a point-in-time ETM image. This cannot be empirically demonstrated because ETM imagery is only captured on 18-day cycles. However, overestimation by AVHRR is most pronounced in the late summer/fall when rainfall is heterogeneous and the landscape is most patchy, lending evidence to support this explanation. Other differences in sensor characteristics could also be contributing to this problem. Xiao and Moody (2005) showed that high resolution NDVI overestimated fractional green vegetation cover in New Mexico. Differences in spatial resolution are not likely to be responsible—local measures from ETM should be more heterogeneous with greater variability than broader scale measures (Turner et al. 1989). Averaging contiguous ETM pixels to construct a 1-km block for comparison with AVHRR data would result in an NDVI that is closer to average, especially in the spring when low and high NDVI values are dispersed across the landscape.

Historically, it was thought that dynamics of woody plant encroachment into grasslands in the southwestern US was a function of ENSO events, yet analysis of long-term vegetation data at the SNWR showed little directional change in the grass–shrub boundary following several ENSO events (Li 2002). Instead, shrub encroachment may result from prolonged changes in precipitation seasonality in addition to interannual fluctuations in total precipitation. Given that winter rains recharge deep soil moisture and that shrubs, such as creosotebush, can use deeper soil moisture when surface soils are dry, a regime shift to more winter precipitation, as has been predicted by climate change models for this region (Houghton et al. 2001), would favor deep-rooted C₃ shrubs over shallowly rooted C₄ grasses that rely on soil moisture primarily from summer rainfall events (Hamerlynck et al. 2002; Schwinning et al. 2003). Thus, a change in

seasonal precipitation regime could lead to shrub encroachment resulting in altered surface and subsurface hydrology (Bhark and Small 2003), reduced biodiversity (Briggs et al. 2005), lower nutrient retention (Schlesinger et al. 1990), altered carbon storage capacity (Jackson et al. 2002), and altered soil resource heterogeneity (Schlesinger et al. 1990).

Arid landscapes are characterized by precipitation events that vary in size, frequency, intensity, duration, and seasonality (Noy-Meir 1973; Porporato et al. 2004; Reynolds et al. 2004; Schwinning and Sala 2004). Community dynamics (Baez et al. 2006) and ecosystem processes (McClain et al. 2003) in arid landscapes are strongly tied to seasonal and annual variation in precipitation. We found that NDVI greenness in this aridland ecosystem was highly variable across space within a given year and over seasonal and annual time frames. Much of this variation was determined by regional climate drivers, such as the North American Monsoon (Gutzler et al. 2002). At the local scale, these regional climate drivers interacted with topography, soils and vegetation to affect patch dynamics and ecosystem processes (Peters et al. 2006). A period of widespread and prolonged drought resulted in a homogeneous distribution of low greenness across the landscape. Although such large, infrequent climatic events may enhance shrub encroachment into grasslands (Peters 2002), the rapid response of both grass and shrub-dominated areas to precipitation following prolonged drought suggests that aridland ecosystems are highly resilient to multi-year drought events. Thus, seasonal shifts in precipitation, in addition to climatic pulses, may be needed for landscape-scale changes, such as shrub encroachment into grassland.

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Appendix 1

Seasonal grouping of imagery for analysis. AVHRR images are 14-day composites repre-

senting 26 periods per year from 1989 to 2005. ETM images are single scenes representing peak productivity in the spring/early summer and late summer/fall seasons over the same time period.

Season	Corresponding dates	AVHRR periods	AVHRR data not included Period: year	ETM images
Spring/ early summer	March 12–July 15	6–14	Missing: 13: 1998	May 15, 1989; May 6, 1990; April 23, 1991; April 8, 1992; May 30, 1993; May 17, 1994; May 20, 1995; June 7, 1996; June 1, 1997; May 3, 1998; May 15, 1999; May 9 2000; June 13 2001; May 15 2002
Late summer/ fall	July 16– November 4	15–22	Missing: 19–22: 1994 Outliers: 15: 1992 15: 2000	Oct 10, 1989; Sep 11, 1990; Sep 30, 1991; Oct 2, 1992; Sep 19, 1993; Aug 21, 1994; Aug 24, 1995; Oct 13, 1996; Sep 14, 1997; Oct 3, 1998; Sep 28, 1999; Sep 14, 2000; Sep 1, 2001; Sep 20, 2002
Winter	November 5– March 11	23–26; 1–5	Missing: 1: 1995 4: 1994 25: 1994 26: 2001 Outliers: 2: 1994 2: 2001 26: 1990	N/A

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