

Assessing the effects of human-induced land degradation in the former homelands of northern South Africa with a 1 km AVHRR NDVI time-series

K.J. Wessels^{a,*}, S.D. Prince^a, P.E. Frost^{b,c}, D. van Zyl^c

^aDepartment of Geography, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, USA

^bCSIR-Satellite Application Centre, Pretoria, South Africa

^cAgricultural Research Council, Institute for Soil, Climate and Water, Pretoria, South Africa

Received 10 December 2003; received in revised form 19 February 2004; accepted 21 February 2004

Abstract

There is a pressing need for an objective, repeatable, systematic and spatially explicit measure of land degradation. In northeastern South Africa (SA), there are large areas of the former homelands that are widely regarded as degraded. A time-series of seasonally integrated 1 km, Advanced Very High Resolution Radiometer (AVHRR) normalized difference vegetation index (NDVI) data was used to compare degraded rangelands [mapped by the National Land Cover (NLC) using Landsat Thematic Mapper (TM) imagery] to nondegraded rangelands within the same land capability units (LCUs). Nondegraded and degraded areas in the same LCU (paired areas) were compared by: (i) testing for differences in spatial mean Σ NDVI values, (ii) calculating the relative degradation impact (RDI) as the difference between the spatial mean Σ NDVI values of paired areas expressed as a percentage of nondegraded mean value, (iii) investigating the relationship between RDI and rainfall and (iv) comparing the resilience and stability of paired areas in response to natural variations in rainfall. The Σ NDVI of degraded areas was significantly lower for most of the LCUs. Relative degradation impacts (RDI) across all LCUs ranged from 1% to 20% with an average of 9%. Although Σ NDVI was related to rainfall, RDI was not. Degraded areas were no less stable or resilient than nondegraded. However, the productivity of degraded areas, i.e., the forage production per unit rainfall, was consistently lower than nondegraded areas, even within years of above normal rainfall. The results indicate that there has not been a catastrophic reduction in ecosystem function within degraded areas. Instead, degradation impacts were reflected as reductions in productivity that varied along a continuum from slight to severe, depending on the specific LCU.

© 2004 Elsevier Inc. All rights reserved.

Keywords: Land degradation; NDVI; Rangelands; South Africa

1. Introduction

Land degradation is believed to be one of the most severe and widespread environmental problems in South Africa (SA; Beinart, 1996; Hoffman et al., 1999; Hoffman & Todd, 2000; SADC–ELMS, 1999) and globally (Dregne et al., 1991; Reynolds & Stafford Smith, 2002; UNCED, 1992). Currently, 184 nations are signatories to the United Nations Convention to Combat Desertification (UNCCD) (UNEP, 1994). However, desertification has proved extremely difficult to quantify and the lack of appropriate data is widely regarded as a major obstacle to progress in this field

(Nicholson et al., 1998; Thomas & Middleton, 1994; Williams & Balling, 1996). Early efforts to map desertification (UNCOD, 1977; UNEP, 1987) have been severely criticized (e.g., Hellden, 1991; Thomas & Middleton, 1994) and recently described by Stocking (2001) as “sterile, inaccurate and misleading”. There is a pressing need for an objective, repeatable, systematic and spatially explicit measure of degradation because its occurrence affects food security, international aid programs, national economic development and natural resource conservation strategies. This has been evident at least since the 1974 drought in the Sahel and the subsequent 1977 United Nations Conference on Desertification (UNCOD, 1977).

Desertification is defined as land degradation in arid, semiarid and dry subhumid areas resulting from various factors including climatic variations and human activities

* Corresponding author. Tel.: +1-301-314-2798; fax: +1-301-314-9299.

E-mail address: wessels@geog.umd.edu (K.J. Wessels).

(UNEP, 1994). Although more than 90% of SA is classified as “affected drylands” (Hoffman et al., 1999), we do not use the term desertification here but prefer “land degradation” because it helps to avoid confusion with the effects of drought and focuses primarily on human impacts. Land degradation has a broad range of definitions (Reynolds, 2001; Thomas & Middleton, 1994) that include, e.g., changes in plant species composition and soil erosion, but essentially describe circumstances of reduced biological productivity of the land (Reynolds & Stafford Smith, 2002; UNEP, 1994). Vegetation production and biomass have been successfully estimated with the normalized difference vegetation index (NDVI) derived from satellite data (Deering et al., 1975; Jury et al., 1997; Myneni et al., 1997; Prince, 1991b; Prince & Tucker, 1986; Tucker & Sellers, 1986). NDVI captures the marked contrast between the strong absorbance in the visible wavelengths and strong reflectance in the near-infrared wavelengths which uniquely characterizes the presence of photosynthetically active vegetation (Tucker, 1979). NDVI has a strong linear relationship with the fraction of photosynthetically active radiation (PAR) absorbed by the plant (f_{PAR} ; Asrar et al., 1984; Goward & Dye, 1987; Kumar & Monteith, 1982; Monteith, 1972, 1977; Sellers, 1987; Sellers et al., 1997) and is routinely employed in production efficiency models (e.g., Behrenfeld et al., 2001; Gower et al., 1999; Field et al., 1995; Potter et al., 1993; Prince, 1991a; Prince & Goward, 1995; Ruimy et al., 1996; Running et al., 1999) where it sets the upper limit for unstressed net primary productivity (NPP; Schloss et al., 1999). In arid and semiarid lands, seasonal sums of multitemporal NDVI are strongly correlated with vegetation production (Prince, 1991b; Prince & Tucker, 1986; Nicholson & Farrar, 1994; Nicholson et al., 1998).

Human-induced land degradation most likely alters the vegetation cover and function before, for example, increasing the extent of soil erosion or changing the local climate through positive feedbacks (Charney et al., 1977; Xue & Fennessy, 2002). If so, changes in f_{PAR} should be among the first factors related to primary production that can alert us to degradation. Therefore, remotely sensed NDVI may provide the basis for an early warning of degradation. NDVI derived from the Advanced Very High Resolution Radiometer (AVHRR) has shown to be capable of systematic, repeatable and spatially extensive monitoring of vegetation productivity to assess desertification (Diouf & Lambin, 2001; Nicholson et al., 1998; Prince & Justice, 1991; Prince et al., 1998; Tucker et al., 1991a,b). The remaining challenge in developing a monitoring approach is how to interpret the NDVI data so that human impacts can be distinguished from both natural spatial variation in the landscape and short-term interannual climate variability that is particularly pronounced in SA due to the El Niño–Southern Oscillation (ENSO) phenomenon (Anyamba & Eastman, 1996; Anyamba et al., 2002; Jury et al., 1997). To address this issue, we compared a time-series of seasonally integrated 1 km

AVHRR NDVI of well-known degraded rangelands with nondegraded rangelands with the same climate and soils. To this end, we (i) quantified the difference in integrated NDVI of degraded and nondegraded areas and (ii) compared the resilience and stability of vegetation production in degraded and nondegraded areas to natural rainfall variability.

2. Background

In SA, communal areas consist of the former self-governing territories or “homelands” and are predominantly populated by black South Africans, engaged in the production of crops and livestock mainly for own consumption or for sale on local, informal markets. In these communal areas, the land is owned by the State. In contrast, commercial areas consist of land that is privately owned by mainly white farmers who market their produce through the formal commercial sector (Hoffman & Todd, 2000). Communal areas have a long history of environmental and political neglect that can be traced back to the 1960’s, the 1930’s or even colonial times (Ross, 1999). These areas have been subjected to overutilization owing to the high human populations that were involuntarily resettled and confined to these relatively small areas (Fig. 1; Fox & Rowntree, 2001; Ross, 1999). Between 1960 and 1985, more than 3.5 million people were forcibly relocated under the Nationalist party’s policy of “apartheid” or separate development (Hoffman et al., 1999). By 1994, 80% of South Africa’s total population had access to only 13% of the land (Kerr Watson, 2001). Stable communities were uprooted and compelled to settle in areas where the inevitable, unsustainable land use degraded the local resource base upon which their rural livelihoods depended (Fox & Rowntree, 2001; Shackleton et al., 2001). Today, communal areas are generally characterized by high human populations, overgrazing, soil erosion, excessive wood harvesting and increases in unpalatable plant species (Hoffman & Todd, 2000). Live stock numbers in communal areas are 2–4 times higher than the recommended stocking rates and twice that of commercial farms (Meadows & Hoffman, 2002; Shackleton, 1993).

As part of SA’s effort to develop a National Action Plan in accordance with the UNCCD, Hoffman et al. (1999) prepared the “National Review of Land Degradation in South Africa” (NRLD). The NRLD was based on a systematic survey (Liniger & Van Lyden, 1998) of the perceptions of 453 agricultural extension workers and resource conservation technicians about the degradation status of 367 magisterial districts. From these surveys, various indices of the severity, extent and rates of different types of degradation (such as reduced vegetation cover, plant species composition and bush encroachment) were estimated. Districts dominated by communal land tenure, i.e., the former homelands, were reported to be moderately to severely degraded (Fig. 1) and are therefore a source of major concern (Hoffman & Ashwell, 2001; Hoffman & Todd, 2000).

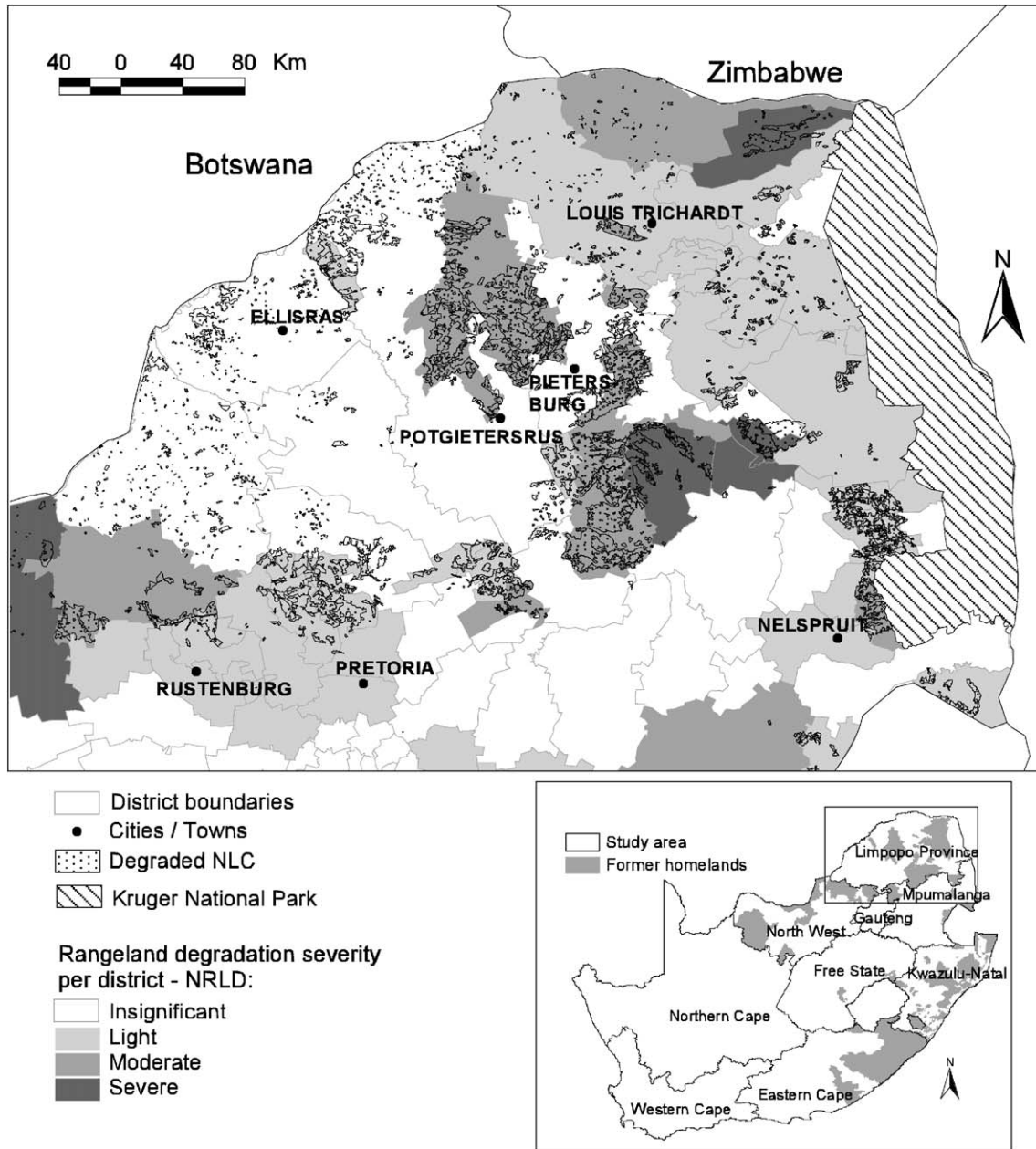


Fig. 1. Study area indicating severity of rangeland degradation per district according to National Review of Land Degradation (after Hoffman et al., 1999). Insert—provinces of South Africa with location of study area and former homelands.

Independently, a National Land Cover map (NLC) was prepared using 1995–1996 Landsat Thematic Mapper (TM) data, manual photointerpretation and extensive fieldwork (Fairbanks et al., 2000). A total of 4.8% (5.8 million ha) of the country was mapped as degraded. The degraded classes in the NLC were defined as regions with lower vegetation cover than surrounding areas (Thompson, 1996), and by far, the greatest areas of extensively degraded land coincided with the moderately to severely degraded communal lands identified by the NRLD (Fig. 1).

The current study assessed the vegetation production of areas mapped as degraded by NLC using 1 km AVHRR

data. Many of these degraded areas are adjacent to apparently nondegraded commercial rangelands, thus allowing the comparison of sites that differ primarily in land management and condition, rather than soils and climate. Because both the NLC and NRLD depended primarily on expert interpretation, and thus also considerable subjectivity in the absence of sufficient biophysical measurements, as did the GLASOD program (Oldeman et al., 1990), these surveys are not sufficiently repeatable for regular land condition monitoring. However, these two studies greatly facilitate the evaluation of remote sensing-based techniques because there is a severe shortage of empirical ecological

studies (e.g., Parsons et al., 1997; Ward et al., 1998) in the communal areas (Shackleton, 1993).

3. Materials and methods

3.1. Study area

The northeastern part of SA, which includes the entire Limpopo Province (formerly Northern Province) as well as parts of the Mpumalanga and North-West Provinces (approx. 200,000 km²) was chosen because it includes many of the most extensively degraded areas according to NLC and NRLC (Fig. 1; Botha & Fouche, 2000; Hoffman & Ashwell, 2001). Land use in this region includes commercial and subsistence cultivation, exotic forestry plantations, national parks (e.g., Kruger National Park), private game reserves, commercial cattle ranching and communal grazing. The natural vegetation varies from indigenous forest to open grasslands but primarily comprises savanna woodlands and thickets. This study was only concerned with areas covered by natural vegetation (according to NLC) that are used for grazing wild and domestic animals. Mean annual precipitation ranges from approx. 300 mm along the northern border with Zimbabwe to 1600 mm on the escarpment.

3.2. One kilometer AVHRR data processing

The AVHRR instruments are carried onboard the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. Daily AVHRR High Resolution Picture Transmission (HRPT, 1.1 km resolution) data were received by the Satellite Application Centre (SAC) at Hartebeeshoek SA and processed by the Agricultural Research Council, Institute for Soil, Climate and Water (ARC-ISCW). Data from 1985 to 2003 were processed consistently and calibrated to correct for sensor degradation and satellite changes (Rao & Chen, 1995, 1996). Due to the failure of NOAA13, data for 1994 were unavailable.

The daily images were geometrically corrected by, firstly, using the values of orbital parameters and, secondly, an automated georeferencing system based on 300 ground control image subsets. Images were processed to the Plate Carrée map projection at 1 km². Although atmospheric correction of time-series AVHRR data is desirable for interannual comparison of NDVI data (Cihlar et al., 2004; El Saleous et al., 2000; Huete & Tucker, 1991; Justice et al., 1991), no atmospheric correction was performed because atmospheric water vapor and aerosol optical depth data were not available for the entire time-series at sufficiently high resolution—for example, National Center for Environmental Prediction (NCEP) precipitable water vapor data are only available at a 2.5°×2.5° resolution (Cihlar et al., 1997, 2001, 2004;

DeFelice et al., 2003). A cloud mask was applied based on channel 1, channel 4 and the difference between channels 4 and 5 (Agbu & James, 1994). NDVI was calculated from the red (0.55–0.68 μm) and near-infrared (NIR; 0.73–1.1 μm) bands [$NDVI = (NIR - Red) / (NIR + Red)$].

Ten-day maximum NDVI value composites were calculated to remove residual clouds and reduce atmospheric effects and the influence of varying solar zenith angles (Holben, 1986). Several other procedures have been described that remove noise caused by cloud contamination, atmospheric perturbations or variable solar zenith angles from time-series data (Swets et al., 1999; Viovy & Arino, 1992; Yang et al., 1998). Here, a statistical filter was applied to interpolate cloud flagged or atmospherically affected data, identified whenever a relative decrease in the signal of 5% or more was followed within 4 weeks by an equivalent increase (Lo Seen Chong et al., 1993). The 10-day composites were weighted by the number of days in each composite and summed over the entire growing season, October to April (hereafter referred to as ΣNDVI; Fig. 2; Diouf & Lambin, 2001; Goward et al., 1985; Lo Seen Chong et al., 1993; Prince, 1991b; Yang et al., 1998). The abovementioned 10-day compositing, data interpolation and growth season sum procedures all contributed to reducing the atmospheric effects. However, interannual comparisons of ΣNDVI may be influenced by the remaining atmospheric effects (Cihlar et al., 2004; Justice et al., 1991). Fortunately, most of the comparisons of degraded and nondegraded areas outlined below were on an annual basis and it was reasonable to assume that the ΣNDVI of these adjacent areas were

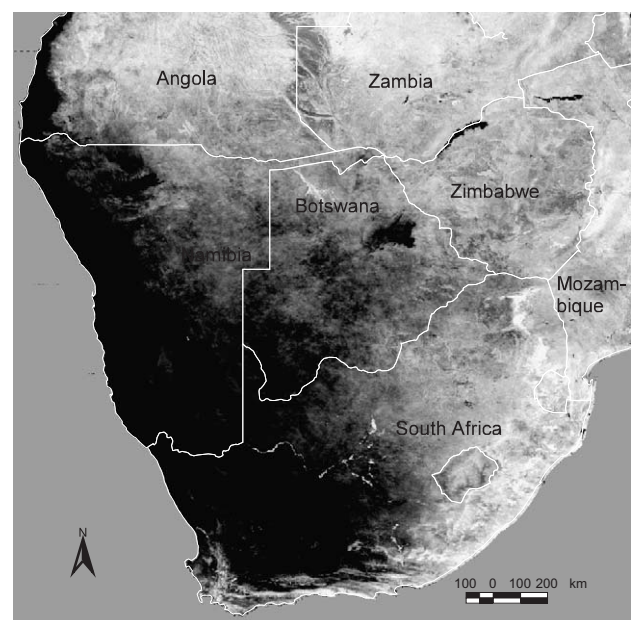


Fig. 2. Grayscale ΣNDVI of Southern Africa for 1998–1999.

equally affected by the atmosphere in any given growth season.

3.3. Comparison of degraded and nondegraded rangelands

For this study, the NLC (Fairbanks et al., 2000) was used to identify degraded rangelands (hereafter referred to only as degraded areas) and nondegraded rangelands. The NLC was also used to include only natural vegetation in the analyses and exclude all other land uses (e.g., informal settlements, urban areas, cultivation and commercial forestry). The classification accuracy of the NLC was assessed using field surveys (approximately 1400 sites in the study area) and aerial photography. The overall mapping accuracy for the study area ranged from 75% to 86% with a Kapa index of 68 to 80, and thus provided the best regional reference data currently available (Fairbanks et al., 2000).

In order to isolate the impact of degradation from spatial variation in soils, topography and climate, the study area was stratified into areas with similar environmental characteristics (Bastin et al., 1995; Karfs et al., 2000). Land capability units (LCUs, described below) were used for stratification to ensure that areas of contrasting land condition (degraded vs. nondegraded) were comparable in all other respects. The expected Σ NDVI values were estimated as the mean of all the values observed in nondegraded areas of the same LCU (e.g., Stoms & Hardgrove, 2000).

Nondegraded and degraded areas in the same LCU (hereafter referred to as paired areas) were compared by: (i) testing for differences in spatial mean Σ NDVI values, (ii) calculating the relative degradation impact (RDI) as the difference between the spatial mean Σ NDVI values of paired areas expressed as a percentage of nondegraded mean value, (iii) investigating the relationship between RDI and rainfall and (iv) comparing the resilience and stability of paired areas in response to rainfall variation. These comparisons were based on the assumption that the LCUs are sufficiently homogenous, so that variations in Σ NDVI could be attributed to human impacts rather than natural landscape, soil and climate variation within the units.

3.4. Land capability units (LCUs) and climate data

The LCUs do not consider current vegetation cover, land use or land condition, making it possible to distinguish natural physical variations from human influences. Land capability is a widely used concept in agricultural development and it refers to the ecologically sustainable suitability of the land for a specific use (e.g., cultivation, grazing or wildlife ranching; Klingebiel & Montgomery, 1961; Vink, 1975). Land units with similar potential and physical limitations, such as climate or susceptibility to soil erosion, are grouped into land capability classes. The land capability data applied here are used by the SA National Department of Agriculture (NDA) for land use

planning purposes (Schoeman et al., 2002). The physical properties used in mapping the land capability units included: (i) terrain: slope length and gradient; (ii) soil: depth, texture, erodibility, internal drainage, mechanical limitations and acidity derived from the comprehensive land type database (Land Type Survey Staff 1977–2000; MacVicar et al., 1977; USDA, 1992); (iii) climate: moisture availability, length of moist and temperate seasons derived from 1 km² climate surfaces that were modeled from the measurements of a network of approximately 2000 weather stations (Monnik, 2001; Schoeman et al., 2002). Strata were created from individual, contiguous LCU polygons to reduce the possibility that adjacent polygons may have the same calculated land capability rating but for very different reasons (Fig. 3). Only LCUs containing large degraded areas according to the NLC were considered in this study.

Weather stations falling within or close to each of the selected LCU were identified (Fig. 3). The average total growing season precipitation (Oct–Apr) was calculated for all stations located in or near each LCU ($N=1-10$).

3.5. Testing for differences in Σ NDVI of nondegraded and degraded areas

The nonparametric Wilcoxon's rank sum test was applied to test if the median difference between annually paired nondegraded (nd) and degraded (d) Σ NDVI was larger than zero ($H_1: \Sigma$ NDVI_{nd}– Σ NDVI_d>0, $N=16$). Resulting P -values indicate the probability that the median differences were equal to zero ($H_0: \Sigma$ NDVI_{nd}– Σ NDVI_d=0; Table 1).

3.6. Relative degradation impact

The means of all the Σ NDVI pixel values in the degraded or nondegraded parts of a specific LCU were first calculated. The relative degradation impact (RDI) was then calculated as the difference between the nondegraded (nd) mean Σ NDVI and degraded (d) mean Σ NDVI expressed as a percentage of the nondegraded mean Σ NDVI value for a specific growth season (Eq. (1)).

$$RDI = (\Sigma NDVI_{nd} - \Sigma NDVI_d) / \Sigma NDVI_{nd} \times 100 \quad (1)$$

For every growth season, this provided a measure of the impact of degradation relative to the expected nondegraded mean value for each LCU. This variable nondegraded baseline effectively accounted for interannual variability in growing conditions experienced by the paired areas.

3.7. Σ NDVI–rainfall relationship

To investigate the relationship between Σ NDVI and growth season rainfall (Rainfall_{*t*}), correlation coefficients and linear regression models were computed for every LCU. The potential influence of interannual lags in

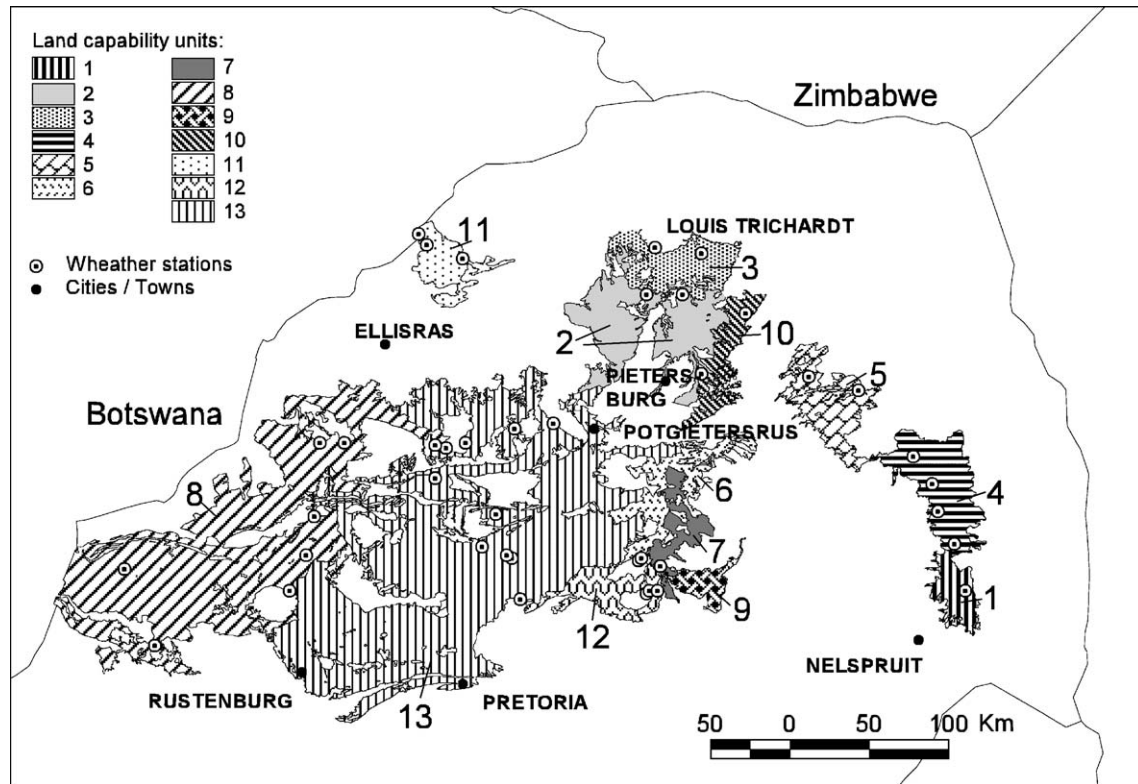


Fig. 3. Selected land capability units (LCU) and weather stations used to calculate mean growth season rainfall for each LCU.

vegetation response to rainfall was examined by calculating the correlation between the preceding growth season's rainfall (Rainfall_{t-1}) and ΣNDVI_t . Where this correlation was positive, multiple regression models were computed with the dependent variable ΣNDVI_t being determined by the corresponding growth season's rainfall (Rainfall_t) and the preceding growth season's rainfall (Rainfall_{t-1}).

3.8. RDI–rainfall relationship

Comparisons of remote sensing data for dry and wetter years have been used to measure the recovery or resilience of vegetation along grazing gradients and proposed to identify degradation (Bastin et al., 1995; Dube & Pickup, 2001; Pickup & Chewings, 1994; Pickup et al., 1998). Degraded areas are expected to be those where grazing gradients do not diminish following good rainfall. In Australia and Botswana, where this method has been applied, the driver of degradation is the increase in grazing intensity closer to livestock water supplies (Dube & Pickup, 2001; Pickup et al., 1998), while in the current study, abrupt boundaries occur between degraded and nondegraded areas, often owing to boundaries between communal and commercial rangelands. Following the general approach of the resilience method (Pickup et al., 1998), we analyzed the interannual relationship between RDI and rainfall to ascertain if RDI decreases or

remains the same in years with higher rainfall. We therefore tested if the degraded areas were resilient enough to reduce or eliminate the RDI with increased rainfall.

3.9. Ecological stability

Ecological stability refers to the ability of a system to remain the same while external conditions change (Noy-Meir & Walker, 1986). We compared the stability of degraded and nondegraded areas by calculating the percentage departure of a pixel's ΣNDVI value for a specific growth season from the long-term mean value for that pixel. Stability consists of (a) resistance or the ability of vegetation to stay unchanged during a growth season of reduced rainfall and (b) resilience or the ability to recover from the preceding dry growth season after higher rainfall in the following growth season (Carpenter et al., 2001; Grimm & Wissel, 1997; Walker et al., 2002). More stable areas would be expected to have a lower negative percentage departure (higher resistance) in dry year and a higher positive percentage departure in wet year (higher resilience). A non-parametric Wilcoxon's rank sum test was applied to test whether nondegraded areas have higher stability than paired degraded areas across all growth seasons ($N=16$):

$$H_0: m=0; H_1: m>0 \\ m = \text{median } D_{\text{nd}} - D_{\text{d}}$$

Table 1
Results of analyses of Σ NDVI for nondegraded (n) and degraded areas (d) of land capability units

Land capability unit	1		2		3		4		5		6		7		8		9		10		11		12		13	
Land condition	n	d	n	d	n	d	n	d	n	d	n	d	n	d	n	d	n	d	n	d	n	d	n	d	n	d
Average Σ NDVI (1985 to 2003)	74.5	72.0	54.8	47.9	55.0	52.4	71.4	66.9	79.8	68.2	59.6	53.2	59.3	54.9	62.2	60.5	71.4	63.0	66.7	53.3	52.4	51.6	66.7	57.4	64.3	60.9
Standard deviation Σ NDVI (1985 to 2003)	8.9	7.0	6.4	6.3	6.8	6.5	8.5	7.0	8.4	8.1	5.2	5.9	5.4	5.0	8.5	8.8	5.3	5.3	7.2	6.2	6.4	6.3	5.4	4.5	4.9	5.3
Coefficient of variance Σ NDVI	12.0	9.8	11.8	13.2	12.4	12.4	12.0	10.5	10.5	11.9	8.8	11.1	9.1	9.2	13.7	14.6	7.4	8.3	10.9	11.6	12.2	12.3	8.2	7.9	7.6	8.6
Max. Σ NDVI	92.6	87.0	68.8	60.6	69.7	66.5	86.0	78.6	93.7	82.7	66.9	64.2	68.7	63.5	74.5	72.7	80.7	74.8	77.9	64.0	63.7	62.6	73.5	64.3	71.7	68.2
Min. Σ NDVI	59.2	59.8	47.1	38.3	45.0	41.0	57.7	54.6	64.6	54.4	49.4	45.2	50.3	46.9	40.5	37.6	60.7	52.8	55.4	44.9	37.9	40.1	55.5	46.5	53.0	48.3
Mean annual RDI	3.0		12.7		4.7		6.2		14.6		10.9		7.4		3.0		11.8		20.1		1.4		14.0		3.4	
Mean annual rainfall	780.0		455.6		472.9		718.1		718.9		529.0		554.1		594.0		535.9		663.2		491.8		612.8		643.8	
<i>P</i> -value: Wilcoxon's test Σ NDVI (nondegraded vs. degraded)	0.170		0.005		0.140		0.069		0.001		0.003		0.016		0.294		0.000		0.000		0.348		0.000		0.040	
R^2 RDI vs. rainfall	0.040		0.060		0.030		0.057		0.244		0.039		0.019		0.005		0.005		0.145		0.016		0.034		0.228	
Correlation RDI vs. rainfall	0.200		-0.257		0.180		0.240		-0.490		-0.199		0.140		0.070		0.075		-0.380		-0.126		-0.180		-0.470	
Correlation Σ NDVI vs. rainfall	0.557	0.609	0.830	0.816	0.779	0.773	0.769	0.827	0.575	0.654	0.398	0.408	0.688	0.674	0.495	0.463	0.252	0.202	0.537	0.649	0.758	0.721	0.199	0.340	0.491	0.577
R^2 Σ NDVI vs. rainfall	0.311	0.371	0.690	0.666	0.600	0.598	0.592	0.684	0.330	0.428	0.159	0.167	0.474	0.454	0.245	0.215	0.060	0.040	0.289	0.420	0.570	0.520	0.039	0.119	0.241	0.333
<i>P</i> -value: R^2 Σ NDVI vs. Rainfall	0.038	0.020	0.000	0.000	0.001	0.001	0.001	0.000	0.019	0.005	0.177	0.166	0.006	0.008	0.060	0.080	0.360	0.460	0.030	0.006	0.001	0.003	0.450	0.189	0.070	0.030
Correlation Σ NDVI vs. Rainfall _{<i>t</i>-1}	-0.033	-0.352	0.095	0.079	-0.308	-0.24	-0.149	-0.100	0.045	-0.006	0.117	0.073	0.299	0.200	0.267	0.309	0.011	-0.083	0.094	0.1	-0.385	-0.46	-0.223	-0.081	-0.230	-0.057
R^2 Σ NDVI vs. rainfall (multiyear)	NA	NA	0.743	0.731	NA	NA	NA	NA	0.340	0.424	0.021	0.090	0.420	0.378	0.313	0.361	0.020	0.011	0.344	0.486	NA	NA	NA	NA	NA	NA

D_{nd} : percentage departure from long-term average for nondegraded areas

D_d : percentage departure from long-term average for degraded areas

Therefore, we tested if nondegraded areas showed smaller negative departure from their long-term mean (D_{nd}) than degraded areas (D_d ; resistance during drier years) or if nondegraded areas showed larger positive departures (D_{nd}) than degraded areas (D_d) in wetter years following dry years (resilience). The percentage departure therefore measures Σ NDVI relative to the long-term average of that particular pixel, while the abovementioned RDI measures the difference between paired nondegraded and degraded areas for a specific year relative to the nondegraded values of the same year. All the years were included in one analysis to investigate stability through time because both higher resistance and higher resilience of nondegraded areas result in $m > 0$, and paired areas (D_{nd} and D_d) mostly had the same signs, i.e., deviated from the long-term average in the same direction in any given growth season. In isolated cases where D_{nd} and D_d had opposite signs, the departures were close to zero and therefore excluded from the Wilcoxon's test. The interannual coefficient of variation in Σ NDVI provided another measure of ecological stability of paired areas (Noy-Meir & Walker, 1986).

4. Results

4.1. Differences between nondegraded and degraded areas

Degraded areas had lower Σ NDVI than their paired nondegraded area across all growth seasons and LCUs (Fig. 4A) with very few exceptions (e.g., LCU 11 and LCU 1 during the very dry 1991–1992 and 2002–2003 growth seasons). The degree of overlap in values for degraded vs. nondegraded areas (indicated by error bars in Fig. 4A) also varied between LCUs and there was still substantial variation in most LCUs (Fig. 4A). Fig. 5 gives the average Σ NDVI (1995–2000) for the nondegraded areas of each LCU to illustrate the differences between LCUs (coefficient of variance=12.7%) and emphasizes the importance of detailed stratification.

P -values derived from the Wilcoxon's test denote the probability that the median difference in Σ NDVI between paired areas was equal to zero ($H_0: m=0$; Table 1). LCUs 2, 5, 6, 7, 9, 10, 12, 13 had $P < 0.05$ indicating a 95% probability that nondegraded areas have significantly higher Σ NDVI values. Two other LCUs (1 and 3) had probabilities of 83% and 85%, respectively, while nondegraded areas in LCUs 8 and 11 were not significantly different (Table 1).

4.2. Relative degradation impact (RDI)

The average RDI values (Table 1) indicate that the Σ NDVI of degraded areas were between 1% and 20%

lower than the nondegraded areas. LCUs 5, 10 and 12 had the highest average RDI values of 14.6%, 20.1% and 14.0%, respectively. LCUs 1, 8 and 11 had the lowest average RDI values of 3%, 3% and 1.4%, respectively. The average RDI of all the LCUs was approximately 9%, indicating the average reduction in Σ NDVI caused by degradation. When LCUs 1, 8 and 11 were excluded, the average RDI was 11.4%. In most cases, the RDI did not show any obvious directional trends through the entire time-series (Fig. 4B). Although degradation may have intensified in specific parts of an LCU, this did not increase the RDI, which was calculated for all the pixels in each LCU. LCUs 2, 5, 6, 7, 9, 10, 12 and 13 showed an increase in RDI from the 1999–2000 to the 2002–2003 growth season, but this may be attributed to a sharp decrease in rainfall during this period (discussed below).

4.3. Σ NDVI–rainfall relationship

The average growth season rainfall for the selected weather stations ($N=151$) within the study area (Fig. 6) indicate that the study period captured the most extreme rainfall years in the past 35 years. 1991–1992, 1994–1995 and 1997–1998 were amongst the driest El Niño seasons, while 1999–2000 and 1995–1996 were the wettest and third wettest growth seasons, respectively. The 2001–2002 and 2002–2003 growth seasons have been very dry (Fig. 6). In general, the late 1980s were below average rainfall and, since the early 1990s, oscillations between wet and dry years have been more extreme than any other period in the 35-year record (Fig. 6). The rainfall has a coefficient of variance of 30% overall and 40% since 1990 and, therefore, rainfall is highly variable in the study area.

The differences between Σ NDVI of contrasting rainfall years are shown in Fig. 7. The areas of consistent high Σ NDVI (dark green in Fig. 7) are indigenous forest and exotic forestry plantations along the escarpment (north–south) and the Soutpansberg mountain range (east–west). There was a close spatial coincidence of reduced Σ NDVI in areas mapped as degraded by NLC, especially those north-west of Pietersburg and southeast of Potgietersrus (Fig. 7C). Many of the large areas with low Σ NDVI outside the NLC degraded polygons are subsistence cultivation and not rangeland (Fig. 7C).

The 1991–1992 El Niño caused reduced Σ NDVI values for most LCUs (Fig. 4A). The effects of the 1997–1998 El Niño event (Anyamba et al., 2001) and transition to the 1999–2000 La Niña conditions (Anyamba et al., 2002) on Σ NDVI are clearly visible in Figs. 4A and 7B,C. Although the 1997–1998 El Niño events did not result in severe drought over the entire region (Anyamba et al., 2002), most LCUs (2, 3, 4, 5, 6, 7, 9, 10, 11) showed a marked decline in Σ NDVI (Fig. 4A). The southern part of the study area and the corresponding LCUs 8, 12 and 13 did

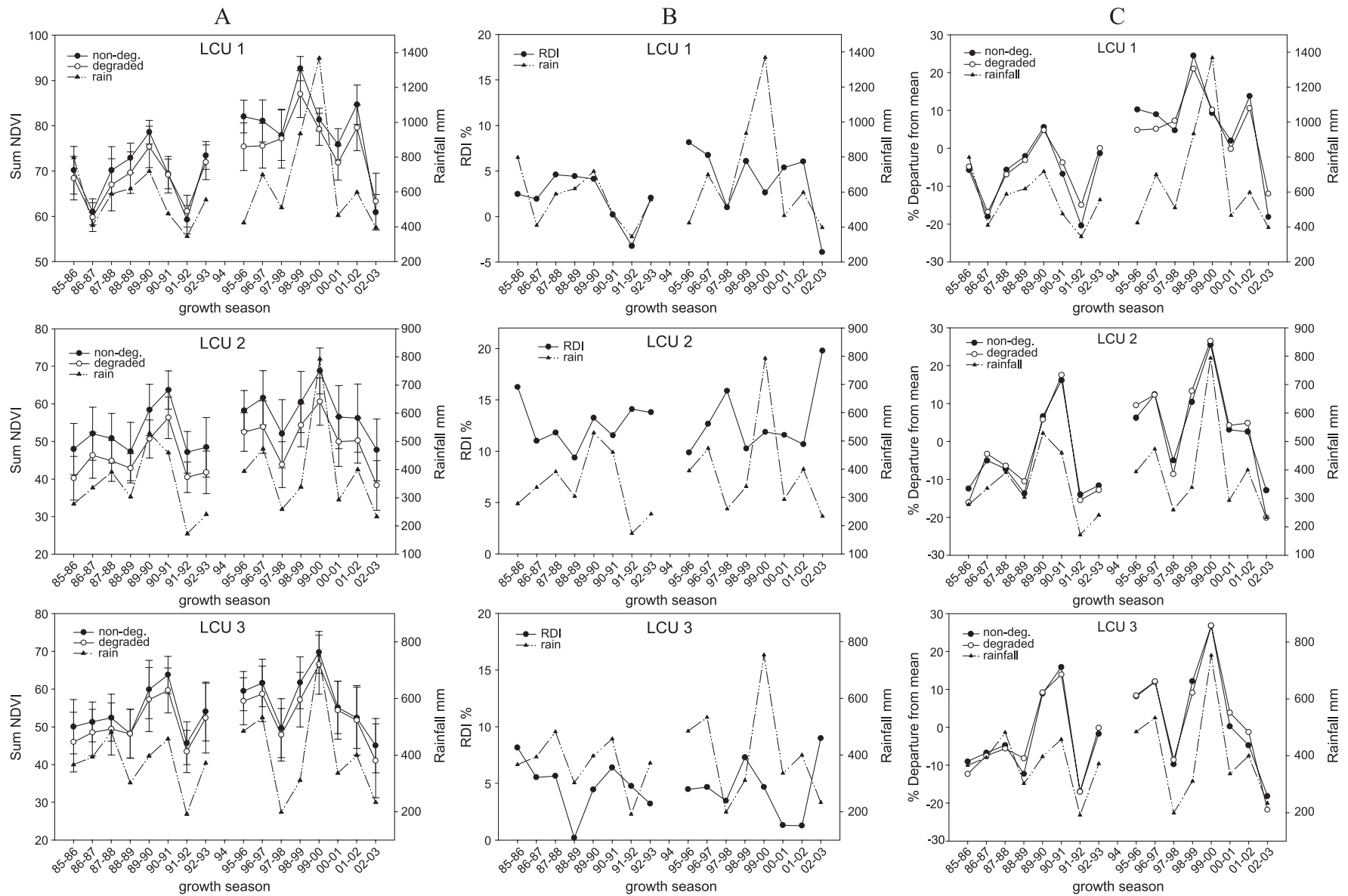


Fig. 4. (A) Σ NDVI and rainfall per growth season for each land capability unit (LCU). Error bars indicate standard deviation. (B) Relative degradation impact (RDI) and rainfall per growth season. (C) Departures from long-term mean Σ NDVI and rainfall per growth season.

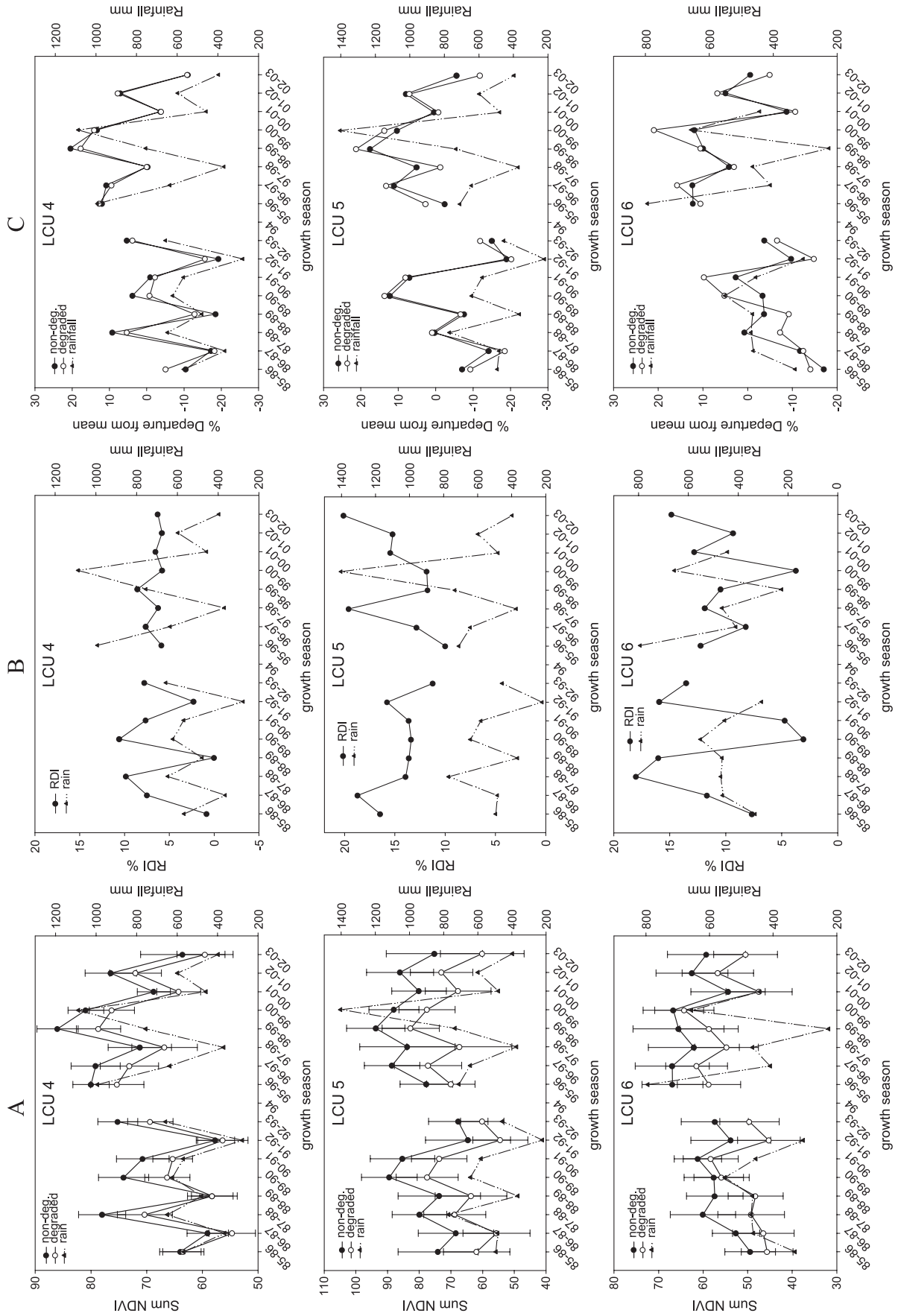


Fig. 4 (continued).

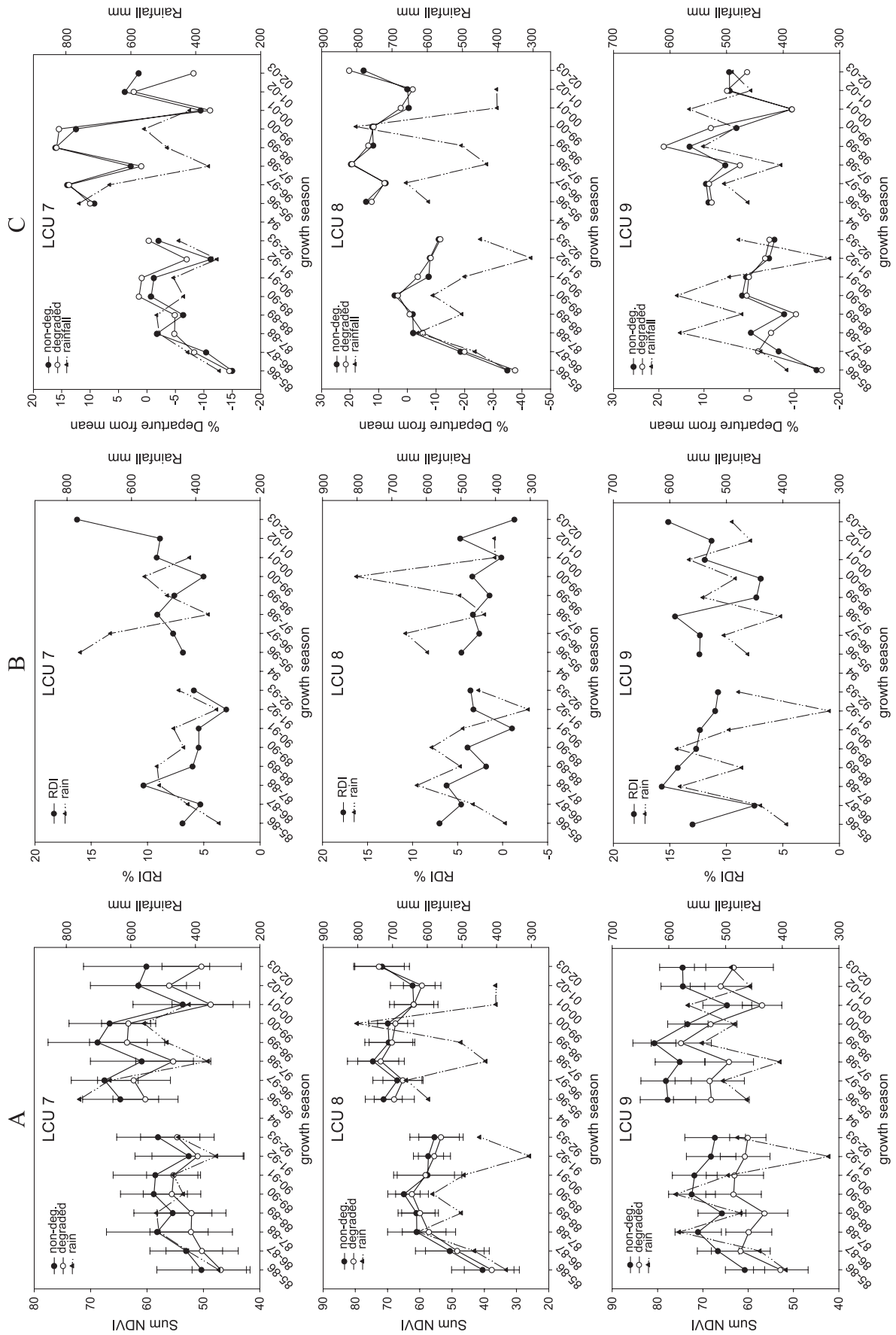


Fig. 4 (continued).

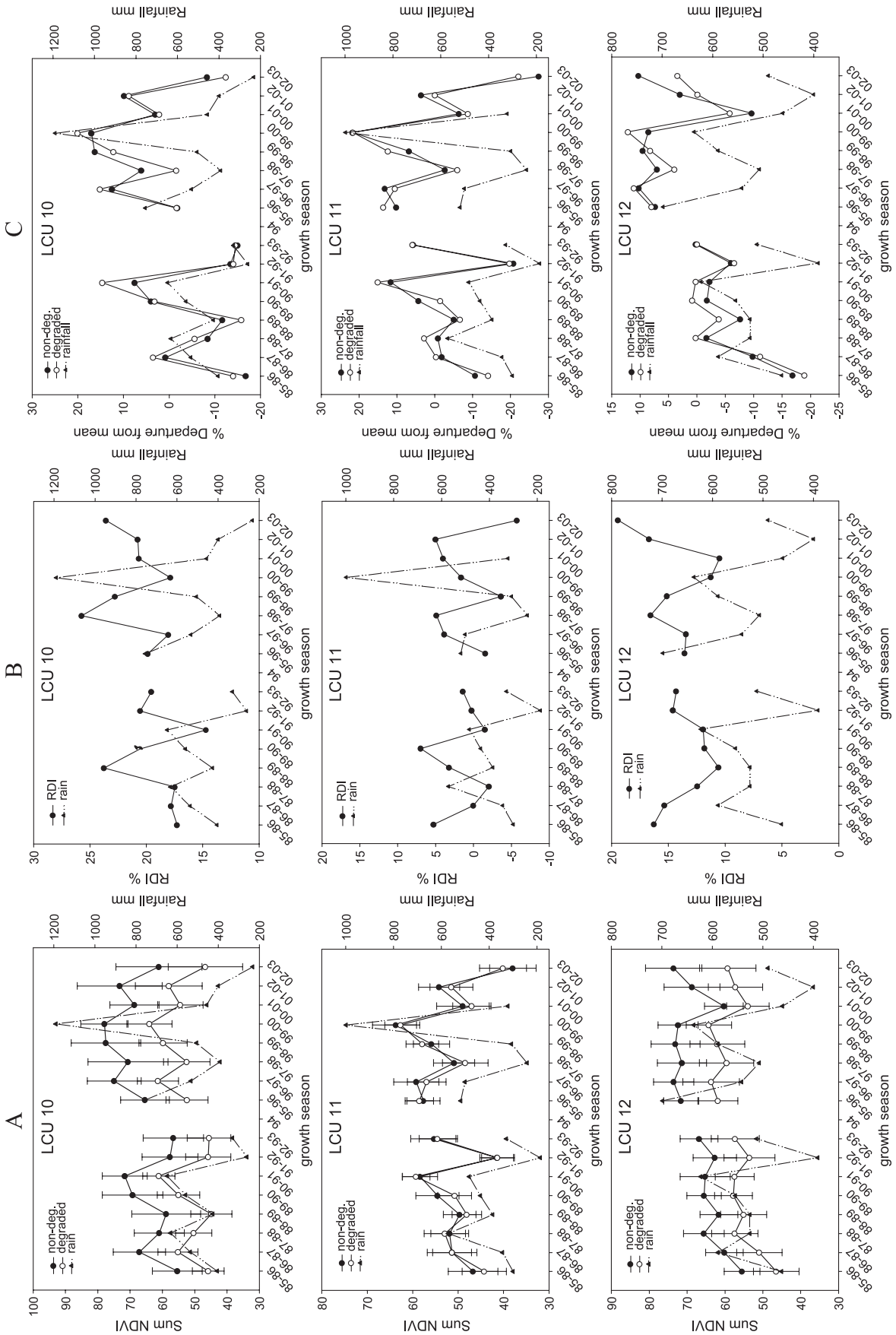


Fig. 4 (continued).

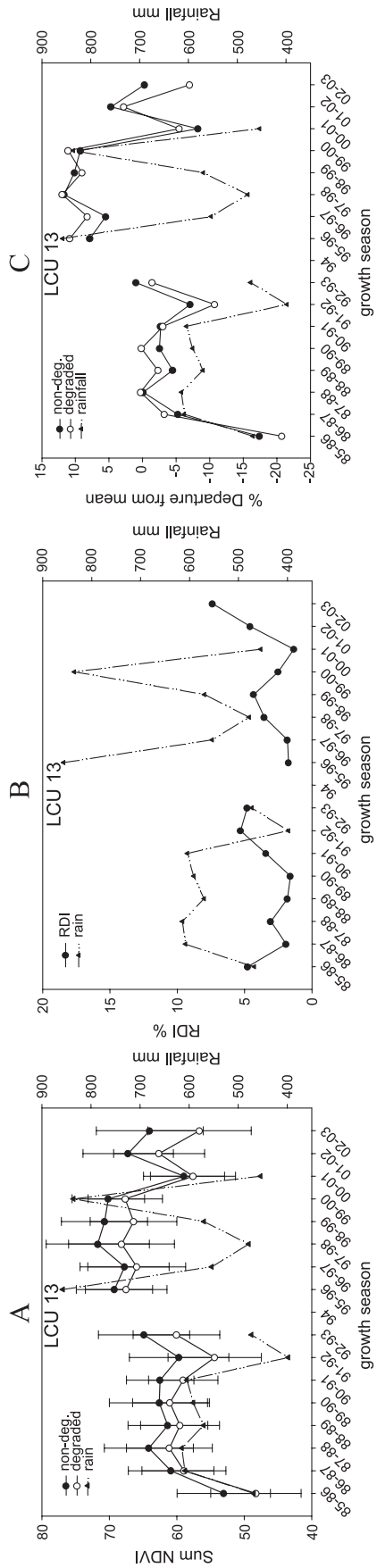


Fig. 4 (continued).

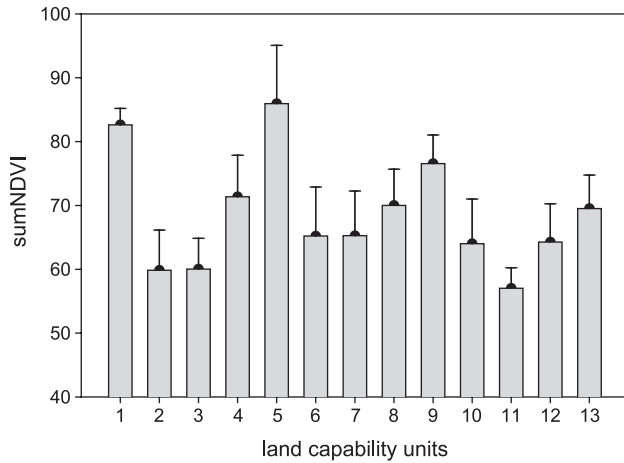


Fig. 5. Average nondegraded Σ NDVI of land capability units for 1995 to 2000. Error bars indicate standard deviation.

not show a decline in Σ NDVI during the 1997–1998 El Niño event (Figs. 4A and 7C). The 1999–2000 La Niña event caused the highest rainfall in recent history and very high Σ NDVI values (Figs. 4A and 7B). The reduction in Σ NDVI showed by LCU 1 in 1999–2000 (Fig. 4A) was most likely caused by the severe flooding in the area.

Variation in growth season precipitation appears to be the proximate cause of the substantial interannual variation in Σ NDVI (Fig. 4A). Degraded areas and paired nondegraded areas showed similar increases in Σ NDVI following good rainfall, although the Σ NDVI values of degraded areas remained consistently lower than those of nondegraded areas of the same growth season (Fig. 4A). LCUs 2, 3, 4 and 11 showed the strongest relationship between Σ NDVI

and Rainfall_t , with $R^2 \geq 0.5$ ($P \leq 0.001$) and LCUs 1, 5 and 7 had moderately strong Σ NDVI– Rainfall_t relationships ($R^2 \geq 0.3$, $P < 0.05$; Table 1).

LCUs 1, 3, 4, 11, 12 and 13 showed negative correlations between Σ NDVI– Rainfall_{t-1} . This unexpected negative relationship was caused by the contrast between the rainfall of successive growth seasons, which often oscillated between very wet and very dry (Fig. 4A). Adding the preceding year's rainfall (Rainfall_{t-1}) to the multiple regression models only slightly increased the percentage of the variance in Σ NDVI accounted for in LCUs 2, 8 and 10. This may indicate that these LCUs experienced a small degree of interannual lag effects between rainfall and vegetation response (Table 1).

4.4. RDI–rainfall relationship

Several LCUs (2, 5, 6, 7, 9, 10) exhibited a common pattern of a peak in RDI during the very dry 1997–1998 El Niño season and a subsequent decrease in RDI following the high rainfalls of 1998–1999 and 1999–2000 growth seasons (Fig. 4B). This was followed by an increase of RDI during the dry 2001–02 and 2002–03 growth seasons (Fig. 4B). This indicated that the relative degradation impact was most pronounced during the dry periods (1997–1998 and 2002–2003) and decreased to some extent during the exceptionally high rainfall growth season (1999–2000). In the same fashion, several LCUs (2, 3, 5, 11, 12, 13) showed a common pattern of elevated RDI during the very dry 1985–1986 and 1986–1987 growth seasons followed by a reduction in RDI corresponding with higher rainfall in 1987–1988 (Fig. 4B).

A regression analysis between rainfall and the RDI for all growth seasons showed that only LCUs 5 and 13 had an

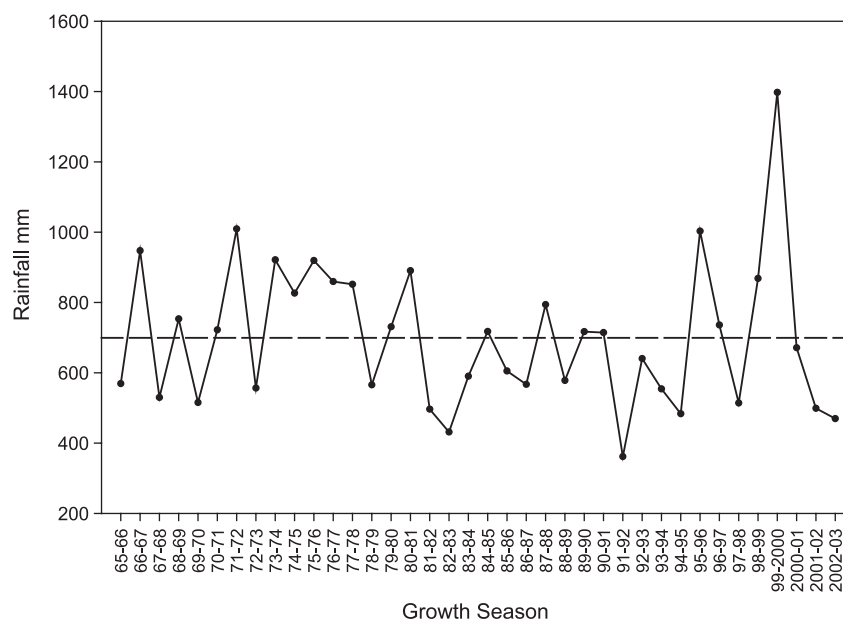


Fig. 6. Mean growth season rainfall for all weather stations ($N=151$) in study area for 1965 to 2003.

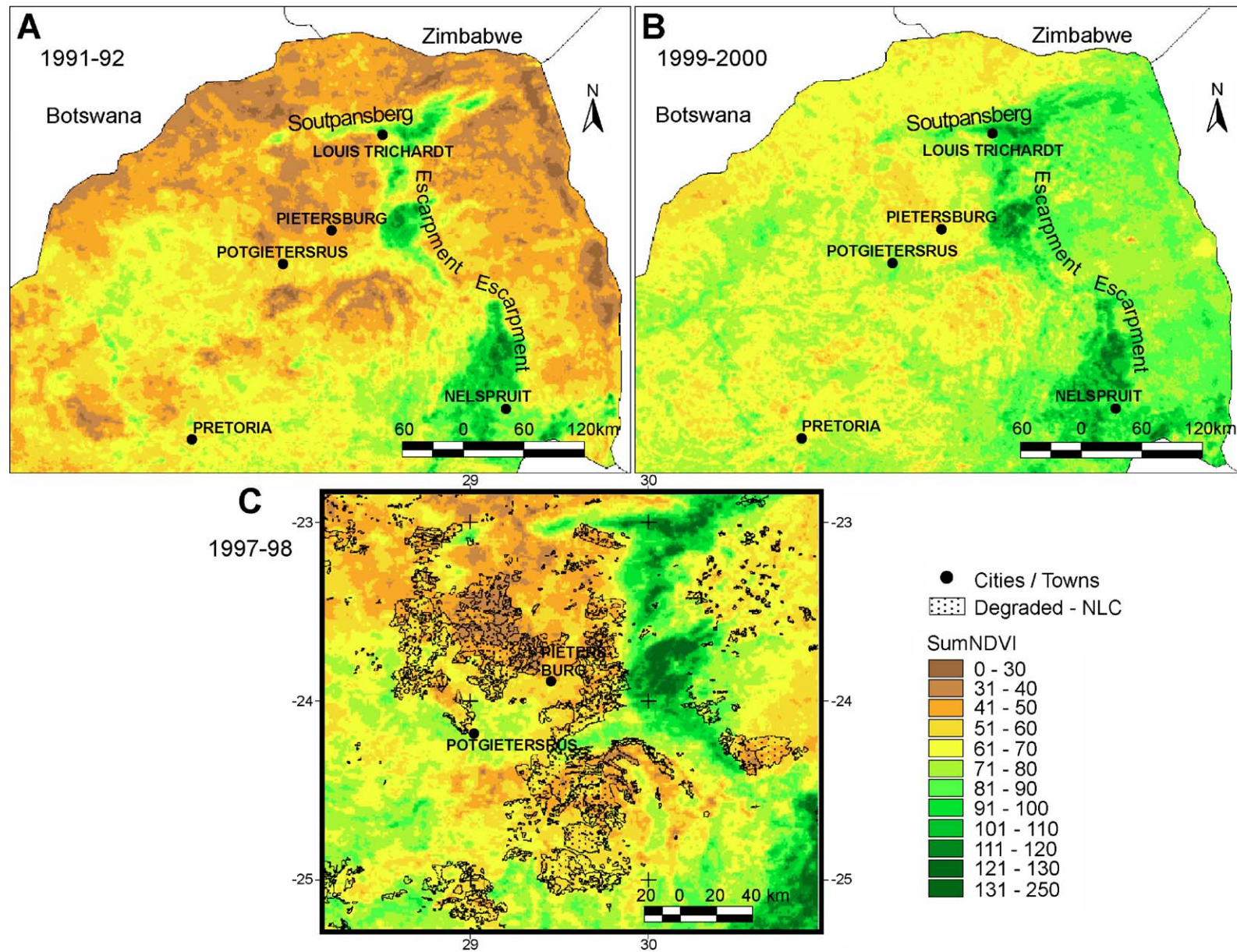


Fig. 7. Σ NDVI of study area for (A) 1991–1992 and (B) 1999–2000. (C) Σ NDVI for central parts of study area (1997–1998) overlaid with degraded areas mapped by National Land Cover (NLC).

$R^2 > 0.2$ (Table 1). For LCUs 2, 5, 6, 10, 11, 12 and 13 the correlations were negative (although weak) indicating that the magnitude of the difference slightly decreases during higher rainfall years (Fig. 4B). The low R^2 values suggests that, for most of the LCUs, the RDI values, i.e., magnitude of difference between degraded and nondegraded, was not strongly related to the rainfall.

4.5. Ecological stability

In agreement with the pattern of slightly smaller RDI in wetter years, the degraded areas in LCUs 5, 6, 7, 9, 10, 12 exhibited slightly less resistance during the 1997–1998 El Niño but slightly more resilience in 1998–1999 or in the 1999–2000 La Niña (Fig. 4C). The degraded and nondegraded areas generally showed very similar departures (Fig. 4C). The results of the Wilcoxon's test showed that, overall, there were no significant difference in the departures, and thus, the stability of paired degraded and nondegraded areas. The interannual coefficient of variation of Σ NDVI ranged from 7% to 14%, with an average of approximately 10% for all the LCUs (Table 1). The coefficients of variation of paired areas were very similar with the biggest difference being 1.9% (Table 1), suggesting that degraded and nondegraded areas exhibited the same level of interannual variation.

5. Discussion

Relative degradation impacts (RDI) across all LCUs ranged from 1% to 20% with an average of 9%, while interannual coefficient of variation Σ NDVI ranged from 8% to 14% with an average of 10.7% (Table 1). The 12.7% coefficient of variance of mean Σ NDVI across all LCUs (Fig. 5) indicates that landscape variability was a large source of natural background variation that was addressed through detailed stratification (Bastin et al., 1995; Dube & Pickup, 2001).

LCUs 5, 10 and 12 showed the highest RDI values, and thus showed the biggest degradation impact. LCUs 2, 5, 10 and 13 showed weak to moderate negative correlation between RDI and rainfall (Table 1), indicating that the degradation impacts were slightly reduced with higher rainfall (Fig. 4B). This is in accordance with other studies in Botswana and Australia where vegetation resilience was investigated using the grazing gradient method (Bastin et al., 1995; Dube & Pickup, 2001; Pickup et al., 1998). In this study, however, the RDI never reached zero as a result of high rainfall (Fig. 4B).

The relationship between Σ NDVI and Rainfall, was generally not as strong as those reported elsewhere (Diouf & Lambin, 2001; Malo & Nicholson, 1990; Nicholson et al., 1998). For some LCUs (i.e., 2, 3, 4, 7 and 11), the R^2 values were relatively high (approx. 0.5, $P < 0.01$; Table 1) and comparable to those reported in the Sahel (Prince et al.,

1998). Different LCUs also demonstrated considerable variation in the strength of the relationship between Σ NDVI and Rainfall. There was no clear relationship between the long-term mean annual rainfall of an LCU and the strength of the Σ NDVI and Rainfall_t relationship (Table 1). In the current study, the primary objective was not to relate rainfall to Σ NDVI of pixels around the weather station as in most previous studies but rather to relate the rainfall to all the pixels in the LCU. This could have reduced the strength of the observed relationship depending on how representative weather stations were of the climate of the specific LCU they were assigned to. Furthermore, the timing and distribution of precipitation throughout the growth season influence vegetation production, but they were not analyzed here. Because Σ NDVI of all growth seasons may not have been affected equally by the atmosphere, this may have further reduced the Σ NDVI–rainfall correlation. Only three LCUs (2, 8 and 10) showed a slight influence of the preceding growth season's rainfall on Σ NDVI. Therefore, in contrast with previous studies, (Diouf & Lambin, 2001; Goward & Prince, 1995; Prince et al., 1998) there was no strong evidence of interannual lag periods in the effects of rainfall on vegetation activity.

The results suggest that degraded areas were no less stable in Σ NDVI than nondegraded areas (Fig. 4C). The interannual coefficients of variation in Σ NDVI of paired areas were within 2% of one another (Table 1), indicating similar variability (Noy-Meir & Walker, 1986). The ecological stability, as measured by the percentage departures from long-term mean of each pixel, showed no difference between degraded and nondegraded paired areas (Fig. 4A). Although the lack of atmospheric correction of the AVHRR data may otherwise complicate the interannual comparison of Σ NDVI, it should not influence the comparison of ecological stability of paired areas because these adjacent areas should experience the same atmospheric effects during any given growth season. Both nondegraded and degraded areas showed remarkable resilience whenever droughts were followed by good rainfall (Fig. 4A). The influence of rainfall was so pronounced that the Σ NDVI of degraded areas in wet years was often much higher than that of nondegraded paired areas in drier years (Fig. 4A). Therefore, the degraded rangelands do not appear to have crossed any critical thresholds to change from a high vegetation biomass state to a low biomass state (Holmgren & Scheffer, 2001; Noy-Meir, 1975). Communal lands have continuously supported large numbers of livestock without any of the catastrophic declines in total numbers predicted during the past six decades (Shackleton, 1993; Tapson, 1991). Apart from instances where livestock declines were attributed to severe drought (Shackleton, 1993), degraded communal areas appear to be functionally stable.

Several definitions of land degradation are based on the loss of resilience and a permanent, irreversible decline in forage output (Abel & Behnke, 1996; Folke et al., 2002; Scheffer et al., 2001). According to these definitions, the

abovementioned results suggest that the areas mapped as degraded by NLC are not necessarily degraded. However, rangeland degradation can more specifically be expressed in terms of productivity, defined as forage production per unit rainfall (Abel, 1997; Pickup, 1996; Walker et al., 2002). In any given year and for a specific amount of rainfall, degraded areas showed lower Σ NDVI (Fig. 4A) and thus reduced productivity. Although some of the results suggest the relative impact of the degradation decreased slightly following high rainfall, the degradation impact never disappeared, not even after the very strong 1999–2000 La Niña event (Anyamba et al., 2002; Fig. 4B). The degraded areas showed an equivalent capacity to recover but very rarely reached the same levels of productivity as those attained by paired nondegraded areas (Fig. 4A). In contrast to previous studies, which used AVHRR NDVI, where apparent “desertification” in Africa could mainly be attributed to droughts (Diouf & Lambin, 2001; Nicholson et al., 1998; Prince et al., 1998; Tucker et al., 1991a), the reductions in Σ NDVI discussed here can be attributed to human-induced land degradation. The relative degradation impact remained fairly consistent for a test period of 16 growth seasons, despite exceptionally high rainfall in the late 1990’s. This might suggest that the reduced productivity has become permanent or very difficult to reverse (Prince, 2002). However, unless the high grazing pressure in communal lands can be removed for a number of years using exclusion plots, the irreversibility of these impacts cannot be unequivocally established (Prince, 2002; Shackleton, 1993).

Because there is a perception that communal rangelands are moderately to severely degraded (Fig. 1; Hoffman & Ashwell, 2001), it may seem surprising that average RDI (i.e., the percentage difference in Σ NDVI values of degraded and nondegraded areas) of all the LCUs is only 9%, with a maximum of 20% (Table 1). Within the context of net primary production (NPP) models (e.g., Prince & Goward, 1995), this would suggest that, if the general climate (air temperature, rainfall and relative humidity) of the paired areas were the same, the f_{PAR} , and therefore, the NPP of degraded areas were on average only 9% less (RDI in Table 1).

There are a number of potential explanations for this apparent disparity in the perceived and the remotely sensed degradation impacts. (i) The detailed stratification applied here allowed a more precise pairing of comparable areas with similar soils and climate, while human observations may compare degraded areas to dissimilar areas with higher potential productivity (Ward et al., 2000). (ii) Qualitative human perceptions of rangeland condition are often based on single annual observations of standing biomass. Biomass is largely determined by grazing intensity and this can be up to four times higher in communal areas (Shackleton, 1993), hence, a lower standing crop is expected. In contrast, NDVI gives a continuous measure of the photosynthetically active radiation absorbed by the vegetation, which may be more closely related to NPP than single observations of accumu-

lated standing biomass that do not account for large differences in herbivory (Scurlock et al., 1999). Much of this uncertainty stems from the lack of sufficient field data or any coordinated long-term field campaigns to compare degraded and nondegraded areas (Shackleton, 1993). (iii) On the other hand, the limited spectral and spatial resolution of AVHRR data may lack the sensitivity required to accurately quantify degradation impacts. Bastin et al. (1995) concluded that the limited dynamic range of AVHRR data within the region of the vegetation response signal considerably diminishes its response to the intensity of grazing impacts when compared to Landsat data. Run-off in degraded landscapes often leads to the accumulation of nutrients and water in lush patches forming a heterogeneous mosaic (Holmgren & Scheffer, 2001). Such finer scale degradation impacts in the landscape may be subsumed within the 1 km² pixels (Bastin et al., 1995; Diouf & Lambin, 2001). In addition, the AVHRR data cannot detect changes in species composition in degraded rangelands towards unpalatable or annual grass species (Hoffman & Ashwell, 2001; Parsons et al., 1997) because these changes are not always associated with a reduction in herbaceous production (Kelly & Walker, 1977).

Regardless of whether or not the AVHRR-derived Σ NDVI underestimates the degradation impact, the results clearly indicate that there has not been a radical shift to a very different state or a catastrophic reduction in ecosystem function within areas mapped as degraded by the NLC (Folke et al., 2002; Holmgren & Scheffer, 2001; Scheffer et al., 2001). Instead, degradation impacts were reflected as reductions in productivity that varied along a continuum from slight to severe, depending on the specific LCU (Tongway & Hindley, 2000). In general, we can conclude that, although the degraded areas are functionally stable and resilient, they show consistent, moderate reductions in forage production per unit rainfall. These results highlight the importance of multitemporal analyses of ecosystem function to understanding land degradation, which has often been limited to a binary degraded/nondegraded classification.

Land redistribution and restitution programs could potentially subject areas currently under commercial management to the socioeconomic driving forces of land degradation (Dean et al., 1996; Fox & Rowntree, 2001; Shackleton et al., 2001) as in Zimbabwe (Prince, in press). Therefore, there is an urgent need for a reliable national monitoring procedure. There have been isolated efforts to map land degradation for specific study areas in SA with Landsat TM (Botha & Fouche, 2000; Kiguli et al., 1999; Tanser & Palmer, 1999). Provincial-scale natural resource audits based on Landsat TM mapping of vegetation cover, field surveys of plant species composition and soil erosion assessments in SA (e.g., Wessels et al., 2000) and elsewhere (e.g., Karfs et al., 2000; Pickup & Smith, 1993; Pickup et al., 1993) have proven to be slow, costly and not sufficiently repeatable for timely national-scale monitoring. Coarse resolution satellite

data, e.g., the AVHRR, SPOT Vegetation and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, provide daily observations and will therefore have to play a central role in monitoring vegetation dynamics and land degradation in SA. Such a coarse resolution remote sensing-based monitoring approach can direct attention to areas where high-resolution remote sensing and field surveys are needed.

Acknowledgements

This work is partially funded by NASA Earth Systems Sciences Fellowship O2-0000-0130 and SA National Department of Agriculture (DoA). We are grateful to Dirk Pretorius (DoA, Directorate: Land Use and Soil Management) and Terry Newby (ARC–ISCW) for making this research possible. Thank you to Johan Malherbe and Gert de Nysschen (ARC–ISCW) for assistance with the climate data and Nicolas Ganzin (GDTA) for software development.

References

- Abel, N. (1997). Mis-measurement of the productivity and sustainability of African communal rangelands: A case study and some principles from Botswana. *Ecological Economics*, 23, 113–133.
- Abel, N., & Behnke, R. (1996). Revisited: The overstocking controversy in semi-arid Africa. *World Animal Review*, 87, 4–27.
- Agbu, P. A., & James, M. E. (1994). *The NOAA/NASA pathfinder AVHRR land data set user's manual*. Greenbelt: Godard Distributed Active Archive Center, NASA, Goddard Space Flight Center.
- Anyamba, A., & Eastman, J. R. (1996). Inter-annual variability of NDVI over Africa and its relation to El Niño/Southern Oscillation. *International Journal of Remote Sensing*, 17, 2533–2548.
- Anyamba, A., Tucker, C. J., & Eastman, J. R. (2001). NDVI anomaly patterns over Africa during the 1997/98 ENSO warm event. *International Journal of Remote Sensing*, 22, 1847–1859.
- Anyamba, A., Tucker, C. J., & Hahoney, R. (2002). From El Niño to La Niña: Vegetation response pattern over East and Southern Africa during the 1997–2000 period. *Journal of Climate*, 15, 3096–3103.
- Asrar, G. M., Fuchs, M., Kanemasu, E. T., & Hatfield, J. L. (1984). Estimating absorbed photosynthetically active radiation and leaf area index from spectral reflectance in wheat. *Agronomy Journal*, 87, 300–306.
- Bastin, G. N., Pickup, G., & Pearce, G. (1995). Utility of AVHRR data for land degradation assessment: A case study. *International Journal of Remote Sensing*, 16, 651–672.
- Behrenfeld, M. J., Randerson, J., McClain, C. R., Feldman, G. C., Los, S. O., Tucker, C. J., Falkowski, P. G., Field, C. B., Frouin, R., Esaias, W. E., Kolber, D. D., & Pollack, N. H. (2001). Biospheric primary production during and ENSO transition. *Science*, 291, 2594–2597.
- Beinart, W. (1996). Environmental destruction in Southern Africa: Soil erosion, animals, and pastures over the longer term. In T. S. Chapman, & G. P. Chapman (Eds.), *Time-scales and environmental change* (pp. 149–167). London: Routledge.
- Botha, J. H., & Fouche, P. S. (2000). An assessment of land degradation in the Northern Province from satellite remote sensing and community perception. *South African Geographical Society*, 82, 70–79.
- Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From metaphor to measurement: Resilience of what to what? *Ecosystems*, 4, 765–781.
- Charney, J., Quirk, W. J., Chow, S. H., & Kornfield, J. (1977). A comparative study of the effects of albedo change on drought in semi-arid regions. *Journal Atmospheric Sciences*, 34, 1366–1385.
- Cihlar, J., Latifovic, R., Chen, J., Trishchenko, A., Du, Y., Fedosejevs, G., & Guindon, B. (2004). Systematic corrections of AVHRR image composites for temporal studies. *Remote Sensing of Environment*, 89, 217–233.
- Cihlar, J., Ly, H., Chen, J., Pokrant, H., & Huang, F. (1997). Multi-temporal, multichannel AVHRR data set for land biosphere studies: Artifacts and correction. *Remote Sensing of Environment*, 60, 35–57.
- Cihlar, J., Tcherednichenko, I., Latifovic, R., Li, Z., & Chen, J. (2001). Impact of variable atmospheric water vapor content on AVHRR data corrections over land. *IEEE Transactions on Geoscience and Remote Sensing*, 39, 173–180.
- Dean, W. R. J., Hoffman, M. T., & Wills, C. K. (1996). The light and the way in South African desertification research. *South African Journal of Science*, 92, 170–172.
- Deering, D. W., Rouse, J. W., Hass, R. H., & Schell, J. A. (1975). Measuring forage production of grazing units from Landsat MSS data. *Proceedings of the 10th International Symposium on remote sensing of environment*, 1169–1178: Ann Arbor, MI, 6–10 October, 1975.
- DeFelicis, T. P., Lloyd, D., Meyer, D. J., Baltzer, T. T., & Piraino, P. (2003). Water vapour correction of the daily 1 km AVHRR global land dataset: Part I. Validation and use of the water vapour input field. *International Journal of Remote Sensing*, 24, 2365–2375.
- Diouf, A., & Lambin, E. (2001). Monitoring land-cover changes in semi-arid regions: Remote sensing data and field observations in the Ferlo, Senegal. *Journal of Arid Environments*, 48, 129–148.
- Dregne, H. E., Kassas, M., & Rozanov, B. (1991). A new assessment of the world status of desertification. *Desertification Control Bulletin*, 20, 6–19.
- Dube, O., & Pickup, G. (2001). Effects of rainfall variability and communal and semi-commercial grazing on land cover in Southern African rangelands. *Climate Research*, 17, 195–208.
- El Saleous, N. Z., Vermotte, E. F., Justice, C. O., Townshend, J. R. G., Tucker, C. J., & Goward, S. N. (2000). Improvements in the global biospheric record from the advanced very high resolution radiometer (AVHRR). *International Journal of Remote Sensing*, 21, 1251–1277.
- Fairbanks, D. H. K., Thompson, M. W., Vink, D. E., Newby, T. S., Van den Berg, H. M., & Everard, D. A. (2000). The South African land-cover characteristics database: A synopsis of the landscape. *South African Journal of Science*, 96, 69–82.
- Field, C. B., Randerson, J. T., & Malmstrom, C. M. (1995). Global net primary production: Combining ecology and remote sensing. *Remote Sensing of Environment*, 51, 74–88.
- Folke, C., Holling, C. S., Walker, B., Carpenter, S., Elmqvist, T., & Gunderson, L. (2002). Resilience and sustainable development: Building adaptive capacity in a world of transformations. *Ambio*, 31, 437–440.
- Fox, R., & Rowntree, K. (2001). Redistribution, restitution and reform: Prospects for the land in the Eastern Cape Province, South Africa. In A. Conacher (Ed.), *Land degradation* (pp. 167–186). London: Kluwer Academic Publishing.
- Goward, S. N., & Dye, D. G. (1987). Evaluating North American net primary productivity with satellite observations. *Advances in Space Research*, 7, 165–174.
- Goward, S. N., & Prince, S. D. (1995). Transient effects of climate on vegetation dynamics: Satellite observations. *Journal of Biogeography*, 22, 549–563.
- Goward, S. N., Tucker, C. J., & Dye, D. G. (1985). North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. *Vegetatio*, 64, 3–14.
- Gower, S. T., Kucharik, C. J., & Norman, J. M. (1999). Direct and indirect estimation of leaf area index, FAPAR, and net primary production of terrestrial ecosystems. *Remote Sensing of Environment*, 70, 29–51.
- Grimm, V., & Wissel, C. (1997). Babel, or the ecological stability discussions: An inventory and analysis of terminology and a guide for avoiding confusion. *Oecologia*, 109, 323–334.

- Hellden, U. (1991). Desertification—time for an assessment. *Ambio*, 20, 372–383.
- Hoffman, M. T., & Ashwell, A. (Eds.) (2001). *Nature divided: Land degradation in South Africa*. Cape Town: Cape Town Univ. Press.
- Hoffman, M. T., & Todd, S. (2000). National review of land degradation in South Africa: The influence of biophysical and socio-economic factors. *Journal of Southern African Studies*, 26, 743–758.
- Hoffman, T., Todd S., Ntoshona Z., & Turner S. (Eds.) (1999). *Land degradation in South Africa*. Cape Town, South Africa: Cape Town National Botanical Institute.
- Holben, B. N. (1986). Characteristics of maximum-value composite images for temporal AVHRR data. *International Journal of Remote Sensing*, 7, 1435–1445.
- Holmgren, M., & Scheffer, M. (2001). El Niño as a window of opportunity for the restoration of degraded arid ecosystems. *Ecosystems*, 4, 151–159.
- Huete, A. R., & Tucker, C. J. (1991). Investigation of soil influences in AVHRR vegetation imagery. *International Journal of Remote Sensing*, 12, 1223–1242.
- Jury, M. R., Weeks, S., & Godwe, M. P. (1997). Satellite-observed vegetation as an indicator of climate variability over Southern Africa. *South African Journal of Science*, 93, 34–38.
- Justice, C. O., Eck, T., Tanre, D., & Holben, B. N. (1991). The effect of water vapor on the normalized difference vegetation index derived for the Sahelian Region from NOAA AVHRR data. *International Journal of Remote Sensing*, 12, 1165–1188.
- Karfs, R., Applegate, R., & Wallace, J. (2000). *Regional land condition and trend assessment in tropical savannas—final report: Audit rangeland monitoring implementation project*. Darwin, Australia: NT Department of Lands Planning and Environment.
- Kelly, R. D., & Walker, B. H. (1977). The effects of different forms of land use on the ecology of the semi-arid region in south-eastern Rhodesia. *Journal of Ecology*, 62, 553–576.
- Kerr Watson, H. (2001). Soil sustainability and land reform in South Africa. In A. Conacher (Ed.), *Land degradation* (pp. 153–166). London: Kluwer Academic Publishing.
- Kiguli, L. N., Palmer, A. R., & Avis, A. M. (1999). A description of rangeland on commercial and communal land, Peddie District, South Africa. *African Journal of Range & Forage Science*, 17, 89–95.
- Klingebiel, A. A., & Montgomery, P. H. (1961). *Land capability classification, agriculture handbook no. 210*. Washington, DC: USDA.
- Kumar, M., & Monteith, J. L. (1982). Remote sensing of plant growth. In H. Smith (Ed.), *Plants and the daylight spectrum* (pp. 133–144). London: Academic Press.
- Land Type Survey Staff (1977–2000). Land types of South Africa on 1:250 000 scale. In *Memoirs of the Agricultural Natural Resource of South Africa, vol. 1–13*. Pretoria: Agricultural Research Council: Institute for Soil, Climate and Water.
- Liniger, L., & Van Lyden, G. (1998). *WOCAT: A framework for the evaluation of soil and water conservation: Questionnaire on the SWC Map (revised edition)*. Bern: Lang Druck.
- Lo Seen Chong, D., Mougin, E., & Gastellu-Etchegorry, J. P. (1993). Relating the global vegetation index to net primary productivity and actual evapotranspiration over Africa. *International Journal of Remote Sensing*, 14, 1517–1546.
- MacVicar, C. N., de Villiers, J. M., Loxton, R. F., Verster, E., Lambrechts, J. J. N., Merryweather, F. R., Le Roux, J., Van Rooyen, T. H., & Harmse, H. J. (1977). Soil classification. A binomial system for South Africa. *Science Bull.*, vol. 390. Pretoria: Agricultural Research Council—Institute for Soil, Climate and Water.
- Malo, A. R., & Nicholson, S. N. (1990). A study of rainfall and vegetation dynamics in the African Sahel using normalized difference vegetation index. *Journal of Arid Environments*, 19, 1–24.
- Meadows, M. E., & Hoffman, M. T. (2002). The nature, extent and causes of land degradation in South Africa: Legacy of the past, lessons for the future. *Area*, 34, 428–437.
- Monnik, K. (2001). Agrometeorological database management strategies and tools in South Africa. In R. P. Motha, & M. V. K. Sivakumar (Eds.), *Software for agroclimatic data management: Proceedings of an expert group meeting. Report WAOB-2001-2* (p. 194). Washington, DC: USDA.
- Monteith, J. L. (1972). Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology*, 9, 747–766.
- Monteith, J. L. (1977). Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London. B*, 281, 277–294.
- Myneni, R., Keeling, C. D., Tucker, C. J., Asrar, G., & Nemani, R. R. (1997). Increased plant growth in northern high latitudes from 1981–1991. *Nature*, 386, 698–702.
- Nicholson, S. E., & Farrar, T. (1994). The influence of soil type on the relationships between NDVI, rainfall and soil moisture in semi-arid Botswana: Part I. NDVI response to rainfall. *Remote Sensing of Environment*, 50, 107–120.
- Nicholson, S. E., Tucker, C. J., & Ba, M. B. (1998). Desertification, drought, and surface vegetation: An example from the West African Sahel. *Bulletin of the American Meteorological Society*, 79, 1–15.
- Noy-Meir, I. (1975). Stability in grazing systems: An application of predator–prey graphs. *Journal of Ecology*, 63, 481–495.
- Noy-Meir, I., & Walker, B. M. (1986). Stability and resilience in rangelands. In P. J. Joss, P. W. Lynch, & O. B. Williams (Eds.), *Rangelands: A resource under siege* (pp. 21–25). Canberra: Australian Academy of Sciences.
- Oldeman, L. R., Hakkeling, R. T. A., & Sombroek, W. G. (1990). *World map on status of human-induced soil degradation (GLASOD)*. Nairobi, Kenya: UNEP/ISRIC.
- Parsons, D. A. B., Shackleton, C. M., & Scholes, R. J. (1997). Changes in herbaceous layer condition under contrasting land use systems in the semi-arid lowveld, South Africa. *Journal of Arid Environments*, 37, 319–329.
- Pickup, G. (1996). Estimating the effects of land degradation and rainfall variation on productivity in rangelands: An approach using remote sensing and models of grazing and herbage dynamics. *Journal of Applied Ecology*, 33, 819–832.
- Pickup, G., Bastin, G. N., & Chewings, V. H. (1998). Identifying trends in land degradation in non-equilibrium rangelands. *Journal of Applied Ecology*, 35, 365–377.
- Pickup, G., & Chewings, V. (1994). A grazing gradient approach to land degradation assessment in arid areas from remotely-sensed data. *International Journal of Remote Sensing*, 15, 597–617.
- Pickup, G., Chewings, V. H., & Nelson, D. J. (1993). Estimating changes in vegetation cover over time in arid rangelands using Landsat MSS data. *Remote Sensing of Environment*, 43, 243–263.
- Pickup, G., & Smith, D. (1993). Problems, prospects, and procedures for assessing the sustainability of pastoral land management in arid Australia. *Journal of Biogeography*, 20, 471–487.
- Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M., Mooney, H. A., & Klooster, S. A. (1993). Terrestrial ecosystem production: A process model based on global satellite and surface data. *Global Biogeochemical Cycles*, 7, 811–841.
- Prince, S. D. (1991a). A model of regional primary production for use with coarse-resolution satellite data. *International Journal of Remote Sensing*, 12, 1313–1330.
- Prince, S. D. (1991b). Satellite remote sensing of primary production: Comparison of results for Sahelian grasslands 1981–1988. *International Journal of Remote Sensing*, 12, 1301–1311.
- Prince, S. D. (2002). Spatial and temporal scales of measurement of desertification. In M. Stafford-Smith, & J. F. Reynolds (Eds.), *Global desertification: Do humans create deserts?* (pp. 23–40). Berlin: Dahlem University Press.
- Prince, S. D. (in press). Mapping desertification in Zimbabwe. In G. Gutman, Anthony Janetos, Christopher O. Justice, Emilio F. Moran, John F. Mustard, Ronald R. Rindfuss, David Skole, & B. L. Turner II. (Eds.), *Land Change Science: Observing, Monitoring, and Under-*

- standing Trajectories of Change on the Earth's Surface.: Kluwer. (Location unknown at present).
- Prince, S. D., Brown de Colstoun, E., & Kravitz, L. (1998). Evidence from rain use efficiencies does not support extensive Sahelian desertification. *Global Change Biology*, 4, 359–374.
- Prince, S. D., & Goward, S. N. (1995). Global primary production: A remote sensing approach. *Journal of Biogeography*, 22, 815–835.
- Prince, S. D., & Justice, C. O. (1991). Coarse resolution remote sensing in the Sahelian environment. *International Journal of Remote Sensing*, 12, 1133–1421.
- Prince, S. D., & Tucker, C. J. (1986). Satellite remote sensing of rangelands in Botswana: II. NOAA AVHRR and herbaceous vegetation. *International Journal of Remote Sensing*, 7, 1555–1570.
- Rao, C. R. N., & Chen, J. (1995). Inter-satellite calibration linkages for the visible and near-infrared channels of the advanced very high resolution radiometer on NOAA-1, -9, and -11 spacecraft. *International Journal of Remote Sensing*, 16, 1931–1942.
- Rao, C. R. N., & Chen, J. (1996). Post-launch calibration of the visible and near-infrared channels of the advanced very high resolution radiometer on the NOAA-14 spacecraft. *International Journal of Remote Sensing*, 17, 2743–2747.
- Reynolds, J.F. (2001). Desertification. In S. Levin (Ed.), *Encyclopedia of Biodiversity*, (vol. 2, pp. 61–78). San Diego: Academic Press.
- Reynolds, J.F., & Stafford Smith, M. (2002). Do humans create deserts? In: Global desertification. *Do humans create deserts?* (pp. 1–22). Berlin: Dahlem University Press.
- Ross, R. (1999). *A concise history of South Africa*. Cape Town: Cambridge University Press.
- Ruimy, A., Dedieu, G., & Saugier, B. (1996). TURC: A diagnostic model of continental gross primary productivity and net primary productivity. *Global Biogeochemical Cycles*, 10, 269–285.
- Running, S. W., Baldocchi, D., Gower, S. T., Turner, D., Bakwin, P., & Hibbard, K. (1999). A global terrestrial monitoring network scaling tower fluxes with ecosystem modeling and EOS satellite data. *Remote Sensing of Environment*, 70, 108–127.
- SADC–ELMS (1999). *SADC sub-regional report on the implementation of the United Nations Convention to Combat Desertification in Southern Africa*. Southern African Development Community–Environment and Land Management Sector. Maseru: Ministry of Environment, Gender and Youth Affairs, Government of the Kingdom of Lesotho.
- Scheffer, M., Walker, B., Carpenter, S., Foley, J. A., & Folke, C. (2001). Catastrophic shifts in ecosystems. *Nature*, 413, 591–596.
- Schloss, A. L., Kicklighter, D. W., & Kaduk, J. (1999). Comparing global models of terrestrial net primary productivity (NPP): Comparison of NPP to climate drivers and the normalized difference vegetation index. *Global Change Biology*, 5, 25–34.
- Schoeman, J. L., van der Walt, M., Monnik, K. A., Thackrah, A., Malherbe, J., & Roux, R. E. L. (2002). *Development and application of a land capability classification system for South Africa—unpublished ARC–ISCW report GW/A/2000/57*. Pretoria: Agricultural Research Council—Institute for Soil, Climate and Water.
- Scurlock, J. M. O., Cramer, W., Olson, R. J., Parton, W. J., & Prince, S.D. (1999). Terrestrial NPP: Toward a consistent data set for global model evaluation. *Ecological Applications*, 9, 913–919.
- Sellers, P., Randall, D. A., Betts, A. H., Hall, F. G., Berry, J. A., Collatz, G. J., Denning, A. S., Mooney, H. A., Nobre, C. A., Sato, N., Field, C. B., & Henderson-Sellers, A. (1997). Modeling the exchanges of energy, water and carbon between continents and the atmosphere. *Science*, 275, 502–509.
- Sellers, P. J. (1987). Canopy reflectance, photosynthesis and transpiration: II. The role of biophysics in the linearity of their interdependence. *Remote Sensing of Environment*, 21, 143–183.
- Shackleton, C. M. (1993). Are the communal grazing lands in need of saving? *Development Southern Africa*, 10, 65–78.
- Shackleton, C. M., Shackleton, S. E., & Cousins, B. (2001). The role of land-based strategies in rural livelihoods: The contribution of arable production, animal husbandry and natural resource harvesting in communal areas in South Africa. *Development Southern Africa*, 18, 581–604.
- Stocking, M. (2001). Agriculture, land degradation and desertification: Concluding comments. In A. Conacher (Ed.), *Land degradation: Sixth meeting of the International Geographical Union's Commission on Land Degradation and Desertification* (pp. 387–390). London: Kluwer Academic Publishing.
- Stoms, D. M., & Hardgrove, W. W. (2000). Potential NDVI as a baseline for monitoring ecosystem functioning. *International Journal of Remote Sensing*, 21, 401–407.
- Swets, D. L., Reed, B. C., Rowland, J. D., & Marko, S. E. (1999). A weighted least-squares approach to temporal NDVI smoothing. *Proceedings of the American Society of Photogrammetric Remote Sensing* (pp. 526–536). Portland, OR: American Society of Photogrammetric Remote Sensing (ASPRS), Washington DC.
- Tanser, F. C., & Palmer, A. R. (1999). The application of a remotely-sensed diversity index to monitor degradation patterns in a semi-arid, heterogeneous, South African landscape. *Journal of Arid Environments*, 43, 477–484.
- Tapson, D. R. (1991). The overstocking and offtake controversy reexamined for the case of KwaZulu. Pastoral Development Network, Paper no. 31a. Overseas Development Institute, London.
- Thomas, D. S. G., & Middleton, N. J. (1994). *Desertification: Exploding the myth*. Chichester: Wiley.
- Thompson, M. (1996). A standard land-cover classification scheme for remote sensing applications in South Africa. *South African Journal of Science*, 92, 34–42.
- Tongway, D., & Hindley, N. (2000). Assessing and monitoring desertification with soil indicators. In O. Arnalds, & S. Archer (Eds.), *Rangeland desertification*, vol. 19 (pp. 89–98). Dordrecht: Kluwer Academic Publishing.
- Tucker, C. J. (1979). Red and photographic infrared linear combinations monitoring vegetation. *Remote Sensing of Environment*, 8, 127–150.
- Tucker, C. J., Dregne, H. E., & Newcomb, W. W. (1991). Expansion and contraction of the Sahara desert from 1980 to 1990. *Science*, 253, 299–301.
- Tucker, C. J., Newcomb, W. W., Los, S. O., & Prince, S. D. (1991). Mean and inter-annual variation of growing-season normalized difference vegetation index for the Sahel 1981–1989. *International Journal of Remote Sensing*, 12, 1133–1135.
- Tucker, C.J., & Sellers, P.J. (1986). Satellite remote sensing of primary production. *International Journal of Remote Sensing*, 7, 1395–1416.
- UNCED (1992). *Managing fragile ecosystems: Combating desertification and drought*. Rep. No. Agenda 21, Chapter 12: United Nations Conference on Environment and Development.
- UNCOD (1977). Plan of action to stop desertification. *Report of the UN conference on desertification*, vol. A/CONF 74/36. Nairobi: UNEP.
- UNEP (1987). Sands of Change. UNEP Environmental Brief No. 2.
- UNEP (1994). United Nations convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa.
- USDA (1992). *National soil survey interpretations handbook*. Washington, DC: USDA.
- Vink, A. P. A. (Ed.). (1975). *Land use in advancing agriculture* (p. 394). Berlin: Springer-Verlag.
- Viovy, N., & Arino, O. (1992). The best index slope extraction (BISE): A method for reducing noise in NDVI time-series. *International Journal of Remote Sensing*, 13, 1585–1590.
- Walker, B. H., Abel, N., Stafford Smith, D. M., & Langridge, J. L. (2002). A framework for the determinants of degradation in arid ecosystems. In J. F. Reynolds, & D. M. Stafford Smith (Eds.), *Global desertification: Do humans create deserts?* (pp. 75–94). Berlin: Dahlem University Press.
- Ward, D., Ngairou, B., & Apollus, A. (2000). Perceptions and realities of land degradation in arid Otjimbingwe, Namibia. *Journal of Arid Environments*, 45, 337–356.

- Ward, D., Ngairorue, B. T., & Kathena, J. (1998). Land degradation is not a necessary outcome of communal pastoralism in arid Namibia. *Journal of Arid Environments*, *40*, 357–371.
- Wessels, K. J., van Den Berg, H. M., & Pretorius, D. J. (2000). Spatial natural resource monitoring in the Mpumalanga Province of South Africa. In E. M. Bridges, I. D. Hannam, L. R. Oldeman, F. W. T. Penning de Vries, S. J. Scherr, & S. Sombatpanit (Eds.), *Response to land degradation*. New Hampshire, USA: Science.
- Williams, M. A., & Balling, R. C. (1996). *Interactions of desertification and climate*. London: Arnold.
- Xue, Y., & Fennessy, M. D. (2002). Under what conditions does land cover change impact regional climate? In J. F. Reynolds, & D. M. S. Smith (Eds.), *Under what conditions does land cover change impact regional climate?* (pp. 59–74). Berlin: Dahlem University Press.
- Yang, L., Wylie, B. K., Tieszen, L. L., & Reed, B. C. (1998). An analysis of relationships among climate forcing and time-integrated NDVI of grasslands over the U.S. Northern and Central Great Plains. *Remote Sensing of Environment*, *65*, 25–37.