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Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa

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Abstract

Advanced Very High Resolution Radiometer (AVHRR), Normalized Difference Vegetation Index data (NDVI, 1 km^2, 1985–2003) and modeled net primary production (NPP, 8 km^2, 1981–2000) data were used to estimate vegetation production in South Africa (SA). The linear relationships of Log$_e$Rainfall with NPP and ΣNDVI were calculated for every pixel. Vegetation production generally had a strong relationship with rainfall over most of SA. Therefore, human-induced land degradation can only be detected if its impacts on vegetation production can be distinguished from the effects of rainfall. Two methods were tested (i) Rain-Use Efficiency (RUE = NPP/Rainfall or ΣNDVI/Rainfall) and (ii) Residual Trends (RESTREND), i.e. negative trends in the differences between the observed ΣNDVI and the ΣNDVI predicted by the rainfall. Degraded areas mapped by the National Land Cover in north-eastern SA had reduced RUE; however, annual RUE had a very strong negative correlation with rainfall and varied greatly between years. Therefore, RUE was not a reliable indicator of degradation. The RESTREND method showed promising results at a national scale and in the Limpopo Province, where negative trends were often associated with degraded areas in communal lands. Both positive and negative residual trends can, however, result from natural ecological processes, e.g. the carryover effects of rainfall in previous years. Thus, the RESTREND

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method can only identify potential problem areas at a regional scale, while the cause of negative trends has to be determined by local investigations.

Keywords: Monitoring; AVHRR; NDVI; Rain-use efficiency; NPP; Communal lands; South Africa

1. Introduction

Vegetation production in arid and semi-arid regions is closely related to the long-term average precipitation (Rosenzweig, 1968; Rutherford, 1980) and inter-annual rainfall variability (Le Houérou et al., 1988), especially in Southern Africa which is strongly affected by the El Niño-Southern Oscillation (ENSO) phenomenon (Jury et al., 1997; Anyamba et al., 2002; Cao and Prince, 2005). Short-term variability in primary production makes it exceedingly difficult to distinguish long-term change as a result of human-induced land degradation from the effects of periodic droughts (Pickup et al., 1998; Dahlberg, 2000; Dube and Pickup, 2001; Prince, 2002). Human impacts are further obscured by spatial variability in topography, soil types, vegetation types and land use.

Land degradation is one of the most serious global environmental issues of our time (Dregne et al., 1991; UNCED, 1992; Reynolds and Stafford Smith, 2002b). Over 250 million people are directly affected by desertification and some one billion people in over 100 countries are at risk (Adger et al., 2000). Land degradation has a broad range of definitions that essentially describe circumstances of reduced biological productivity of the land (UNCCD, 1994; Reynolds and Stafford Smith, 2002). According to the United Nations Convention to Combat Desertification (UNCCD) definition, land degradation can be caused by both human and climate factors (UNCCD, 1994). A number of studies have shown that the perceived desertification in the Sahel (e.g. Lamprey, 1975) can largely be attributed to variations in rainfall rather than human-induced land degradation (Tucker et al., 1991a; Nicholson et al., 1998; Prince et al., 1998; Anyamba and Tucker, 2005; Nicholson, 2005). These studies demonstrated that there was neither a progressive southwards march of the Sahara desert, nor large-scale expansion of less productive land (Tucker et al., 1991a; Nicholson et al., 1998; Anyamba and Tucker, 2005). In order to combat land degradation, countries need spatial monitoring systems that are able to distinguish human impacts on vegetation production from the effects of rainfall variability (Pickup, 1996; UNCCD, 1994).

Various methods have been used to monitor changes in vegetation function based on multi-temporal Advanced Very High Resolution Radiometer (AVHRR) data (Hellden, 1991; Tucker et al., 1991b; Lambin and Strahler, 1994). The results are often dominated by erratic rainfall, associated changes in seasonality and drastic land cover or land use changes (Lupo et al., 2001), which all mask any land degradation that is generally more subtle and gradual. Two methods are explored here to distinguish human-induced land degradation from inter-annual variability in rainfall; (i) Rain-Use Efficiency (RUE = net primary production (NPP)/Rainfall or Normalized Difference Vegetation Index (NDVI)/Rainfall) and (ii) Residual Trends (RESTREND), i.e. negative trends in the differences between the observed ΣNDVI and the ΣNDVI predicted by the rainfall using regressions calculated for each pixel. Both these methods are based on the concept that land degradation causes reductions in vegetation production per unit rainfall as a result of soil erosion, soil degradation, changes in vegetation species composition and increased run-off of water (Pickup, 1996; Walker et al., 2002).

It has been suggested that RUE, the ratio of NPP to precipitation, can normalize the inter-annual variability in NPP caused by rainfall variability and consequently provide an index of degradation that is independent of the effects of rainfall (Nicholson et al., 1998; Prince et al., 1998). Field experiments have shown that degraded rangelands have reduced RUE (Le Houérou, 1984; Noy-Meir, 1985; Le Houérou et al., 1988; Snyman, 1998; Illius and O'Connor, 1999; O'Connor et al., 2001). Therefore, RUE has been proposed as a regional indicator of productivity and land degradation, since it can be derived from remote sensing estimates of production (e.g. NDVI) and rainfall data (Tucker et al., 1986; Justice et al., 1991a; Nicholson and Farrar, 1994; Pickup, 1996; Nicholson et al., 1998; Prince et al., 1998; Paruelo et al., 1999; Diouf and Lambin, 2001; Holm et al., 2003).

Evans and Geerken (2004) described a method that allows individual production–rainfall relationships to be developed for each pixel, after which negative trends in the residuals (observed production − production predicted by rainfall) through time are identified. Human-induced land degradation is often the dominant cause of such negative residual trends. Analysis of the rainfall–production relationship for every pixel accommodates the effects of local variations in slope, soil and vegetation which all have a major influence on the nature of this relationship (Justice et al., 1991a).

A serious problem that has inhibited studies of land degradation is the lack of agreement on the existence and location of large areas of land that have been degraded. As a result, studies often end in discussion about the degree or even the reality of degradation (Prince et al., 1998; Herrmann and Hutchinson, 2005). In the South Africa (SA) native "homelands" were established between 1913 and 1936 and during the apartheid era, 3.5 million African people were involuntarily resettled and confined to these areas (Fig. 1a) (Christopher, 1994; Fox and Rowntree, 2001). Within these communal areas livestock numbers grew to 2–4 times the recommended stocking rates (Shackleton, 1993; Meadows and Hoffman, 2002), causing rangeland degradation and severe soil erosion (Hoffman et al., 1999; Hoffman and Todd, 2000). Extensive degraded rangelands, occurring mostly within the communal homelands, have been reliably mapped by the National Land Cover (NLC) project (Fairbanks et al., 2000) (Fig. 2) and provide an extraordinarily valuable natural experiment where the effects of long-term, heavy utilization of the land can be compared to adjacent, non-degraded areas that are equivalent in all other respects (e.g. soils, local climate and topography) (Wessels et al., 2004).

The objectives of this study were to (i) characterize the relationship between rainfall and satellite-derived estimates of growth season production (NPP and growth season sum NDVI), (ii) compare the RUE values of mapped degraded and non-degraded areas with the same climate and soils in north-eastern SA, (iii) evaluate the inter-annual variability of the RUE values to determine if RUE is a robust index that can be mapped to monitor land degradation, and (iv) evaluate the ability of the RESTRENDS method to detect degradation.

2. Background

2.1. Land degradation in SA

Within Southern Africa land degradation is widely regarded as a severe and widespread environmental problem (Snyman, 1998; Hoffman et al., 1999; Hoffman and Todd, 2000;

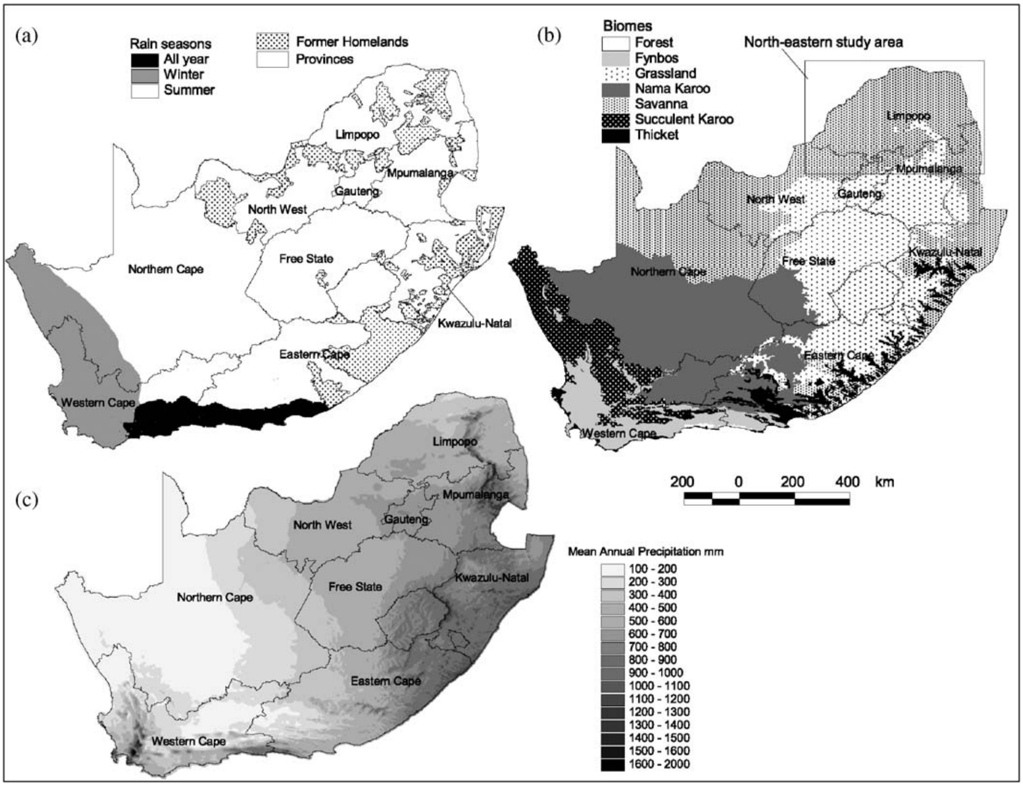


Fig. 1. (a) Rain seasons and former homelands, (b) biomes and (c) average rainfall of South Africa.

Scholes and Biggs, 2004) and in recognition of this issue SA became one of 184 signatory countries to the UNCCD. It has long been speculated that the semi-arid Karoo was expanding north-eastwards into the grasslands as a results of climate change and overgrazing by commercial livestock (Acocks, 1953; Thomas and Middleton, 1992); however, recent reviews found no conclusive evidence of this expansion (Dean et al., 1995).

The SA National Report on Land Degradation (NRLD, Hoffman et al., 1999), based on the qualitative assessments of 453 natural resource conservation officers within each of SA's 367 magisterial districts, directed attention to severe land degradation in the former "homelands", now communal areas (Shackleton, 1993; Hoffman et al., 1999; Hoffman and Todd, 2000; Hoffman and Ashwell, 2001) (Fig. 2). Although degradation also occurs in smaller patches on commercial land and not all parts of the communal lands are degraded, large contiguous degraded areas are predominantly confined to the communal lands (e.g. Fig. 2). The communal areas are characterized by high human and livestock populations, overgrazing, soil erosion, excessive wood removal and the loss of more palatable grazing species, and are thus widely regarded as degraded (Hoffman et al., 1999; Hoffman and Todd, 2000). Degradation threatens the local resource base upon which rural people's communal livelihoods depend (Shackleton et al., 2001). The underlying causes of degradation are a combination of unemployment, poverty and an absence or failure of regulatory structures (Hoffman and Todd, 2000; Scholes and Biggs, 2004).

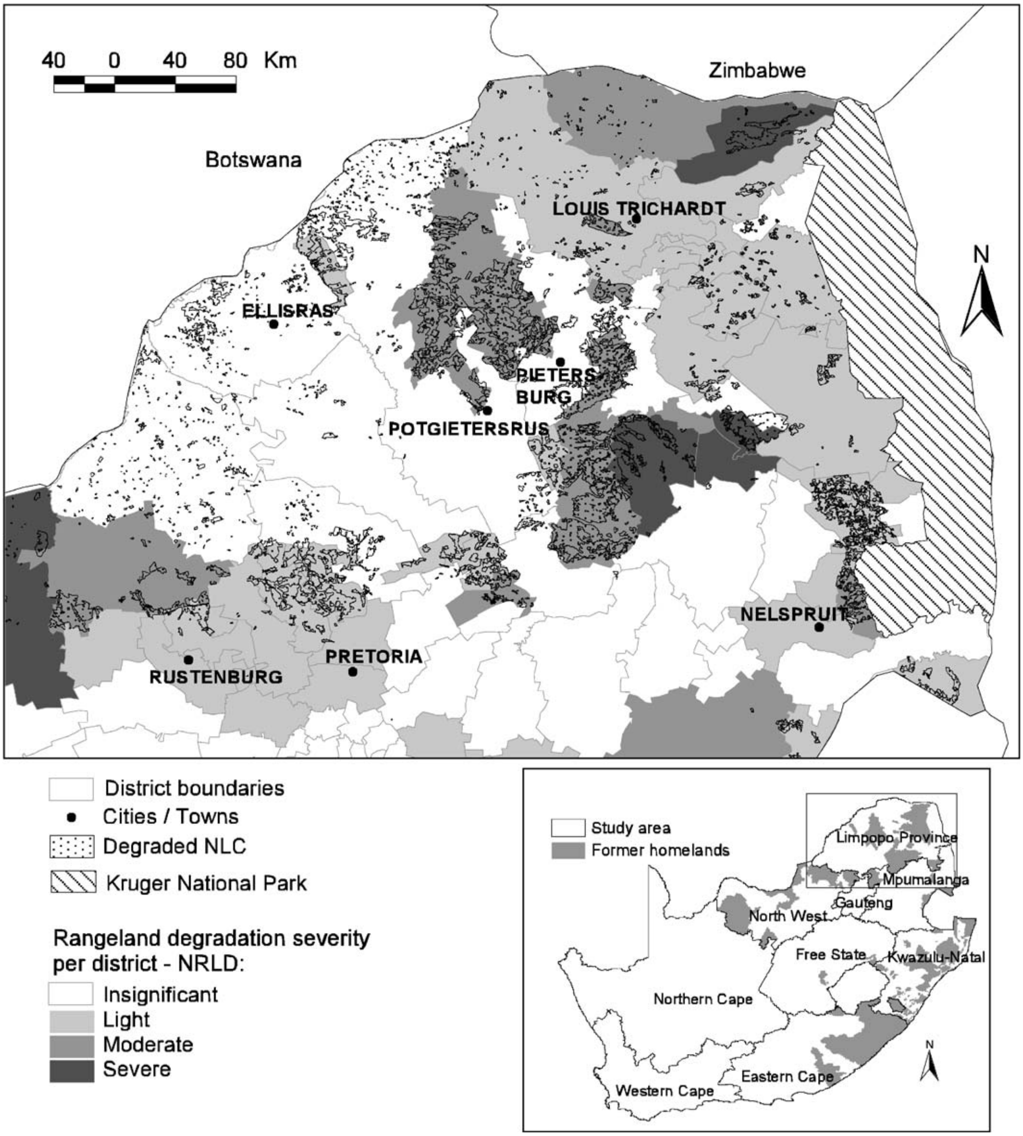


Fig. 2. Study area indicating severity of rangeland degradation per district according to National Review of Land Degradation (Hoffman et al., 1999) overlaid with degraded areas mapped by the National Land Cover (Fairbanks et al., 2000). Inset—Provinces of South Africa with location of study area.

Current land redistribution programs in SA could potentially expose productive lands to the socio-economic driving forces of land degradation (Dean et al., 1996; Fox and Rowntree, 2001). Land degradation affects food security, international aid programs, national economic development and natural resource conservation strategies and therefore there is an urgent need for a national land degradation monitoring system.

2.2. Remote sensing estimates of vegetation production and land degradation

In arid and semi-arid lands seasonal sums of multi-temporal NDVI are strongly correlated with vegetation production (Prince and Tucker, 1986; Prince, 1991b; Nicholson and Farrar, 1994; Nicholson et al., 1998; Wessels et al., 2006). Thus NDVI data derived from the AVHRR sensor have been widely used to assess desertification (Prince and Justice, 1991; Tucker et al., 1991a, b; Nicholson et al., 1998; Prince et al., 1998; Diouf and Lambin, 2001; Anyamba and Tucker, 2005; Olsson et al., 2005). Recently, Wessels et al. (2004) showed that forage production of degraded rangelands, as estimated by NDVI summed over the growth season, was consistently less than that of non-degraded rangelands in any given growth season, despite large inter-annual fluctuations in rainfall.

Satellite data can be used in production efficiency models to estimate NPP at global or regional scales (Prince, 1991a; Prince and Goward, 1995; Gower et al., 1999; Running et al., 1999; Behrenfeld et al., 2001). These models are based on the concept of light-use efficiency, and they use the strong linear relationship between NDVI and the fraction of photosynthetically active radiation (PAR) absorbed by the plant (f_{PAR}) to set the upper limit for unstressed NPP. Spatial data for stress factors such as air temperature, vapor pressure deficit and soil moisture are used in various ways to convert the potential gross production into actual NPP (Cramer et al., 1999; Gower et al., 1999). In this study, both 1 km resolution AVHRR NDVI and modeled 8 km resolution NPP were used to estimate vegetation production. The former has the advantages of computational simplicity and higher spatial resolution, while the latter has the advantage of taking various climatic factors (e.g. rainfall and air temperature) into account to estimate actual NPP in $\mathrm{g\,m^{-2}}$.

Although severe degradation that causes species change in arid areas is sometimes associated with a reduction in vegetation cover which is detectable with remote sensing (Pickup et al., 1994; Wessels et al., 2001), this is not always the case (Kelly and Walker, 1977; Parsons et al., 1997; Diouf and Lambin, 2001). Therefore, some aspects of degradation, such as species change, cannot be monitored with coarse resolution satellite data. Unfortunately, there has not been any coordinated effort to monitor vegetation composition at the national scale and thus the true extent of species change in SA's rangelands remains uncertain. Increases in the density of woody vegetation (bush encroachment) is regarded as a serious form of land degradation in some parts of SA (Hoffman et al., 1999), but can also not be addressed directly using remotely sensed productivity metrics. Radiative transfer models and field observations have, however, shown that the herbaceous layer in savanna woodlands dominates the signal detected by AVHRR or other sensors, especially during the growth season (Prince, 1987; Fuller et al., 1997; Wessels et al., 2004, 2006). Remotely sensed vegetation production may very well be the single most useful indicator of land degradation at regional and decadal scales (Pickup et al., 1994; Prince, 2002).

3. Materials and methods

3.1. Study area—summer rainfall region of SA

The analyses were based on the summer growth season (October–April) and excluded the winter rainfall region (April–September) along the western coast and the year-round rainfall region on the southern coast of SA (Fig. 1a). The summer rainfall region includes the Nama Karoo, Savanna, Grasslands and Thicket biomes (Fig. 1b) and therefore the vast majority of SA rangelands. Mean annual precipitation varies greatly along an east–west gradient from 1000 mm along the east coast and escarpment to only 200 mm in the Northern Cape Province (Fig. 1c). Exotic forestry plantations are located along the high-rainfall areas of the escarpment and parts of the Kwa-Zulu Natal Province. Dryland crop cultivation is largely limited to the grassland biome (Fairbanks et al., 2000), while cattle, game, sheep and goat livestock farming is the dominant land use throughout the rest of the summer rainfall region.

3.2. *NPP data*

NPP was calculated using the Global Production Efficiency Model (GLO-PEM) (Prince and Goward, 1995). For details on the most recent version of the GLO-PEM model and input data used see (Goetz et al., 2000; Cao et al., 2004). The NPP data are freely available from www.glcf.umiacs.umd.edu/data/glopem/.

Total growth season NPP (October–April of following year) was calculated from the 10-day NPP estimates for 1981–82 to 1999–2000 ($N = 19$). The spatial patterns of total above and below-ground NPP predicted by the GLO-PEM model agreed very well with the above-ground NPP estimated by Schulze (1997) using Rosenzweig's (1968) approach.

3.3. *1 km AVHRR NDVI data*

Daily AVHRR High Resolution Picture Transmission (1.1 km resolution) data were received by the Satellite Application Centre 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 and Chen, 1995; Rao and Chen, 1996). Due to the failure of NOAA13, data for 1994 were unavailable. Although atmospheric correction of time-series AVHRR data is desirable for inter-annual comparison of NDVI data (El Saleous et al., 2000; Cihlar et al., 2004), no atmospheric correction was performed since atmospheric water vapor and aerosol optical depth data were not available for the entire time-series at sufficiently high resolution. NDVI was calculated from the red (0.55–0.68 μm) and near infrared (NIR; 0.73–1.1 μm) bands ($\text{NDVI} = (\text{NIR-Red})/(\text{NIR} + \text{Red})$).

Ten day maximum NDVI value composites were calculated to remove residual clouds and reduce atmospheric effects (Holben, 1986). 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 composite NDVI was weighted by the number of days used in each composite and summed over the entire growing season ($N = 16$), October to April (hereafter referred to as ΣNDVI) (Prince, 1991b; Lo Seen Chong et al., 1993; Diouf and Lambin, 2001). The compositing, data interpolation and growth season sum procedures all help reduce the atmospheric effects. However, the multi-temporal ΣNDVI data may be influenced by remaining atmospheric factors and changes in solar-zenith angle due to drifts in the overpass time (Justice et al., 1991b; Cihlar et al., 2004). Despite these potential sources of error, the ΣNDVI data used here have proven to be highly correlated with annual field measurements of herbaceous biomass (1989–2003) (Wessels et al., 2006).

3.4. Rainfall data

The rainfall data were recorded by a network of approximately 1800 weather stations managed by the SA Weather Service and ARC-ISCW (Monnik, 2001). For each station the long-term mean rainfall was calculated for every 10-day period of the year. Ten-day climatological mean rainfall surfaces were then created using multiple linear regression models with independent variable layers such as altitude, distance from ocean, local variation in elevation, latitude, longitude (Malherbe, 2001). To produce a date-specific, 10-day rainfall surface, the percentage of the 10-day long-term mean rainfall received during the specific period was calculated for every weather station. These percentage deviations were interpolated using inverse distance weighting. The resulting deviation layers were then multiplied by the long-term 10-day mean rainfall layers (Malherbe, 2001). The total sum of summer growth season rainfall (October–April; hereafter referred to only as rainfall) was used here, since it has a strong relationship with growth season sum NDVI (Prince et al., 1998; Yang et al., 1998; Wang et al., 2001).

3.5. Relationship of NPP and ΣNDVI with rainfall

Since vegetation production may not continue to increase linearly at high rainfall, a Log_e transformation was applied to the rainfall values (Rutherford, 1980; Milich and Weiss, 2000). The relationships of NPP and ΣNDVI with Log_eRainfall (hereafter referred to only as Rainfall) were characterized using least square regression analyses on a per-pixel basis. The coefficients of determination (R^2) were mapped to show geographical patterns of the relationships.

The relationships between the inter-annual variability of estimates of vegetation production and that of rainfall were also investigated. The coefficient of variation (CV = standard deviation/mean) of each pixel was calculated for rainfall, NPP and ΣNDVI (Le Houérou et al., 1988; Schulze, 1997). Pixel values of the three CV layers were extracted at 1500 random points throughout the study area. A linear regression analysis based on these values was used to characterize the relationships between the CVs of rainfall and NPP, and rainfall and ΣNDVI.

3.6. Comparison of ΣNDVI-RUE of degraded and non-degraded areas

This analysis was carried out in north-eastern SA which includes the entire Limpopo Province and parts of the Mpumalanga and North-West Provinces (approximately 200 000 km^2) (Fig. 1b). The region includes extensive degraded rangelands in the former homelands and current communal lands (Botha and Fouche, 2000; Hoffman and Ashwell, 2001). The NLC (Fairbanks et al., 2000) was used to map degraded and non-degraded rangelands (Fig. 2). The NLC was produced using visual interpretation of 1995–96 Landsat TM data and extensive fieldwork. The degraded classes in the NLC were defined as regions with higher surface reflectance and lower vegetation cover compared to surrounding areas of similar vegetation (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 using land capability units (LCUs). Land capability is a widely used concept in agricultural development and it refers to the suitability of the land for a specific use (Klingebiel and Montgomery, 1961). Detailed data on the following physical properties were used in mapping the LCUs: (i) terrain: slope length and gradient, (ii) soil: depth, texture, erodibility, internal drainage, mechanical limitations, acidity derived from the comprehensive land type database (MacVicar et al., 1977; Schoeman et al., 2002; Wessels et al., 2004). Contiguous areas with similar potential and physical limitations (e.g. climate or susceptibility to soil erosion) were grouped into LCUs (see Fig. 3 of Wessels et al., 2004). The selected LCUs were sufficiently internally homogenous to allow the RUE of degraded and non-degraded areas within them to be compared.

Preliminary analyses showed that the resolution of the 8 km NPP data was too coarse for this comparison and therefore the 1 km NDVI data were used. The RUE for a specific growth season ($N = 16$) was estimated as the ratio ΣNDVI/Rainfall (hereafter referred to as ΣNDVI-RUE). The spatial average ΣNDVI-RUE was calculated for each paired area and every growth season ($N = 16$). A non-parametric Wilcoxon's rank sum test was applied to test if the median difference between annually paired non-degraded (nd) and degraded (d) RUE values was larger than zero (H_1: $\Sigma\text{NDVI-RUE}_{\text{nd}}$–$\Sigma\text{NDVI-RUE}_{\text{d}} > 0$). Resulting p-values indicate the probability that the median differences were equal to zero (H_0: $\Sigma\text{NDVI-RUE}_{\text{nd}}$–$\Sigma\text{NDVI-RUE}_{\text{d}} = 0$).

The average slopes and intercepts of the ΣNDVI–rainfall regressions were calculated for all the pixels in paired degraded and non-degraded areas to provide another measure of the mean RUE (Rutherford, 1980; Illius and O'Connor, 1999).

3.7. Variability of NPP-RUE in time and space

RUE maps were calculated using the NPP and growth season rainfall (hereafter referred to as NPP-RUE). For this analysis the rainfall data were not Log_e transformed in order to retain the original units, i.e. $\text{g m}^{-2}\,\text{mm}^{-1}$. The NPP-RUE maps for successive growth seasons were compared to test their value as an index of land degradation. NPP-RUE values were regressed on time, i.e. growth seasons 1–19 (1981–82–1999–2000) to investigate trends in NPP-RUE values.

3.8. Identifying long-term trends in ΣNDVI

ΣNDVI values were similarly regressed on time, i.e. growth seasons 1–16, for each pixel. Pixels with significant negative slopes indicate areas that experienced a negative temporal trend in growth season biomass production (Evans and Geerken, 2004).

3.9. Detecting negative trends in the ΣNDVI–rainfall relationships—RESTREND method

The long-term trends in ΣNDVI identified in the above-mentioned analyses contain a significant rainfall signal that, if removed, may allow climate trends to be distinguished from human-induced land degradation (Archer, 2004; Evans and Geerken, 2004). Regressions between ΣNDVI and growth season sum Log_eRainfall were calculated for every pixel. To control the effect of inter-annual variation in precipitation, the differences between the observed ΣNDVI and the ΣNDVI predicted by the rainfall were calculated and the residuals (observed–predicted) regressed on time. The average RESTREND values of paired degraded and non-degraded areas in north-eastern SA were compared.

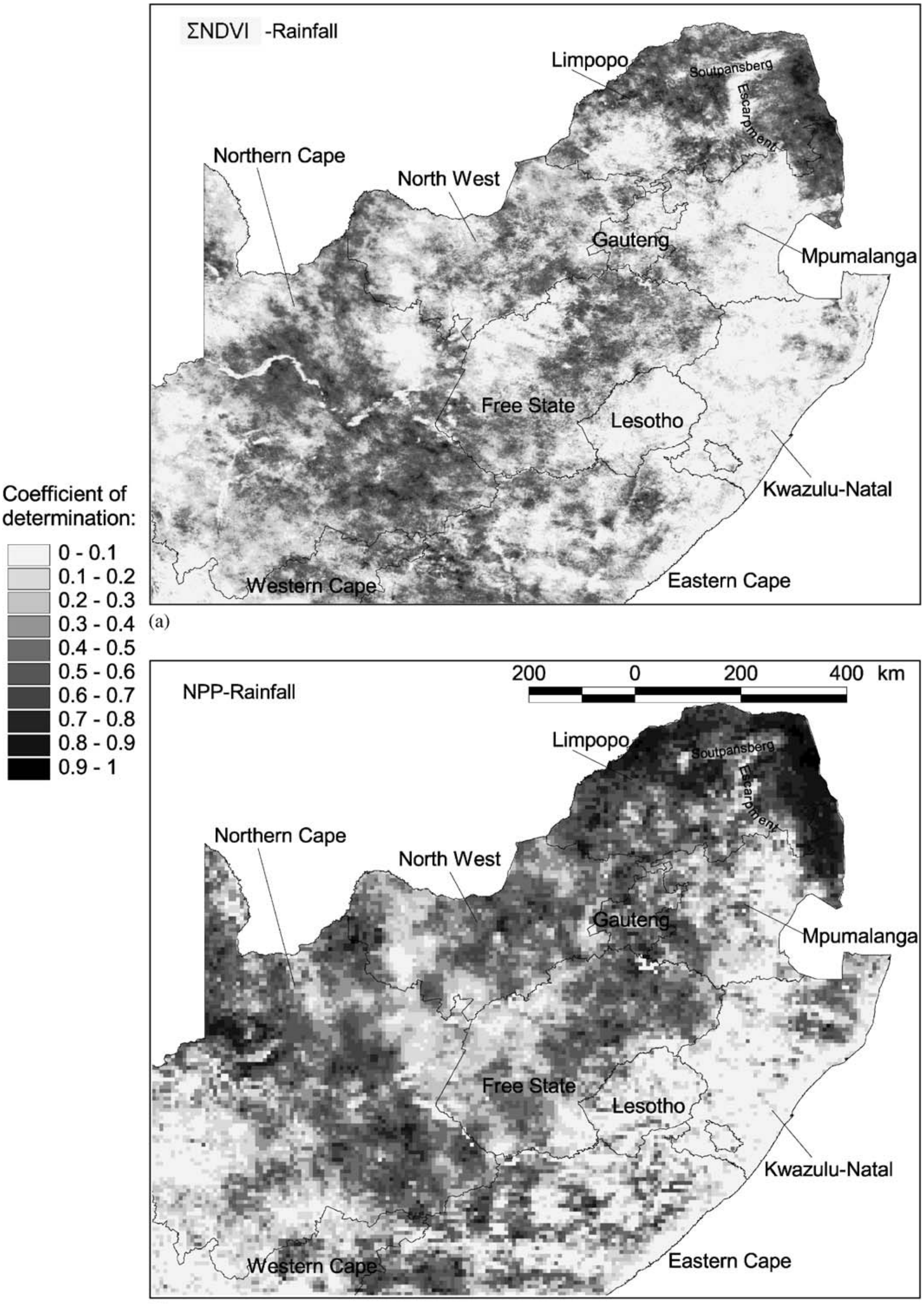


Fig. 3. Maps of coefficients of determination ($R2$) for (a) ΣNDVI–Log_eRainfall and (b) NPP–Log_eRainfall regressions for the summer rainfall region of South Africa.

4. Results

4.1. Relationship of NPP and ΣNDVI with rainfall

The Rainfall–ΣNDVI (Fig. 3a) and Rainfall–NPP (Fig. 3b) relationships differed in strength, but showed very similar patterns. The Rainfall–NPP relationship was generally the stronger one, as expected, since rainfall affects the physiological as well as the leaf area components of NPP. Critical *t*-values calculated for every pixel indicated that, in general, all the regressions with $R^2 > 0.3$ were significant. The strongest relationships ($R^2 = 0.6-0.9$) were evident in north-eastern Mpumalanga and in most of the Limpopo Province (Figs. 3a, b).

In general, the drier areas (<500 mm e.g. Northern Cape, North-West, Limpopo Provinces) had the strongest, while the wetter areas (>700 mm e.g. Lesotho, Kwa-Zulu-Natal, Mpumalanga Highveld) had the weakest relationships (Figs. 3a, b). The areas with very low R^2 values in Limpopo and Mpumalanga provinces occurred on the wet escarpment and the Soutpansberg mountains that are covered by indigenous forests and commercial plantations of exotic trees. Low R^2 values were evident for the irrigated cultivation along the Orange River and some dryland cultivation in western Free State. Pixels in areas experiencing extreme levels of run-off, e.g. the mountains of Lesotho, had weak rainfall–production relationships (Figs. 3a, b). Some dry areas had very weak relationships that are not related to specific land uses or vegetation types (e.g. Northern Cape; Figs. 3a, b).

The regional patterns of the CVs of rainfall, ΣNDVI and NPP were similar, with an eastward decrease over SA and the lowest values along the wet east coast. There were moderate to strong linear relationships between the CVs of rainfall and ΣNDVI ($R^2 = 0.366$), and rainfall and NPP ($R^2 = 0.58$). There was a strong negative relationship between mean annual precipitation and the CVs of rainfall ($R^2 = 0.85$), NPP ($R^2 = 0.5$) and ΣNDVI ($R^2 = 0.3$).

4.2. Comparison of ΣNDVI-RUE of degraded and non-degraded areas

The ΣNDVI-RUE of degraded areas were consistently lower than that of paired non-degraded areas for most LCUs (Fig. 4), with the exception of a few seasons in LCUs 1 and 11. In a Wilcoxon's test of the probability that the median difference in ΣNDVI-RUE between paired areas was equal to zero (H_0: $m = 0$), LCUs 2, 5, 7, 9, 10 and 12 had *p*-values <0.05 indicating significantly higher ΣNDVI-RUE values in non-degraded areas. LCUs 4 and 13 had slightly lower probabilities (92% and 93%, respectively). LCUs 1, 3, 6, 8 and 11 were not significantly different.

ΣNDVI-RUE values were inversely related to rainfall; the highest ΣNDVI-RUE values were observed in the very low rainfall 1991–92 and 1997–98 seasons. The ΣNDVI-RUE values did not show any clear trend through time, but rather fluctuated between growth seasons in step with variations in rainfall.

The intercepts of the regressions of ΣNDVI on rainfall for the non-degraded areas were consistently higher that those of the degraded paired areas, while the slopes were approximately equal (Table 1).

4.3. Variability of NPP-RUE through time and space

The NPP-RUE maps provided regional measures of growth season RUE in $\mathrm{g\,m^{-2}\,mm^{-1}}$ (Fig. 5). The average NPP-RUE (1981–82 to 1999–2000) was lowest in the mountains of

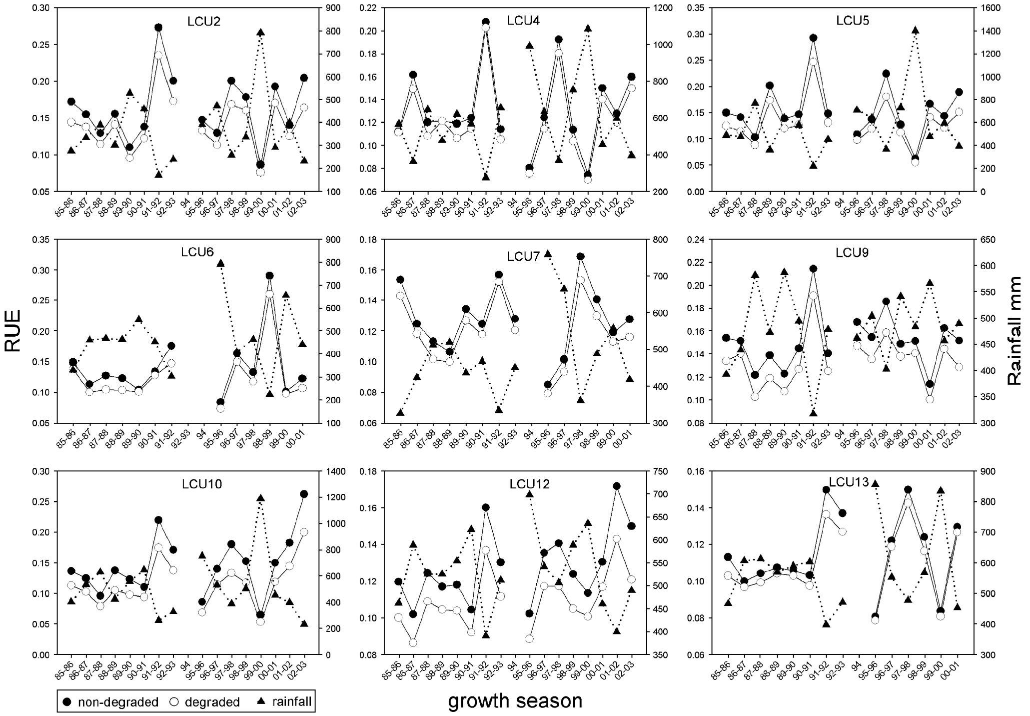


Fig. 4. Average ΣNDVI-RUE of degraded and non-degraded rangelands per growth season, in selected land capability units (LCUs) in north-eastern SA.

Table 1
Average slope and intercept for ΣNDVI–Rainfall relationship and RESTREND values in degraded and non-degraded areas of each land capability unit (LCU)

LCU	Slope		Intercept		RESTREND	
	Non-degraded	Degraded	Non-degraded	Degraded	Non-degraded	Degraded
1	0.019	0.014	61.3	61.5	0.204	0.228
2	0.033	0.033	41.0	34.5	0.213	0.165
3	0.037	0.035	40.3	38.3	0.074	0.076
4	0.027	0.020	54.5	52.4	0.251	0.191
5	0.018	0.023	67.5	53.3	0.148	0.088
6	0.039	0.042	40.0	34.3	0.366	0.270
7	0.039	0.036	39.7	37.4	0.361	0.204
8	0.029	0.028	45.8	44.4	0.276	0.278
9	0.026	0.027	54.8	47.1	0.398	0.402
10	0.014	0.020	57.8	42.7	0.195	0.180
11	0.033	0.030	38.3	38.7	0.030	0.046
12	0.025	0.022	52.0	44.8	0.481	0.484
13	0.018	0.025	53.7	46.9	0.408	0.309

The number of pixels varied between degraded and non-degraded areas of each LCU.

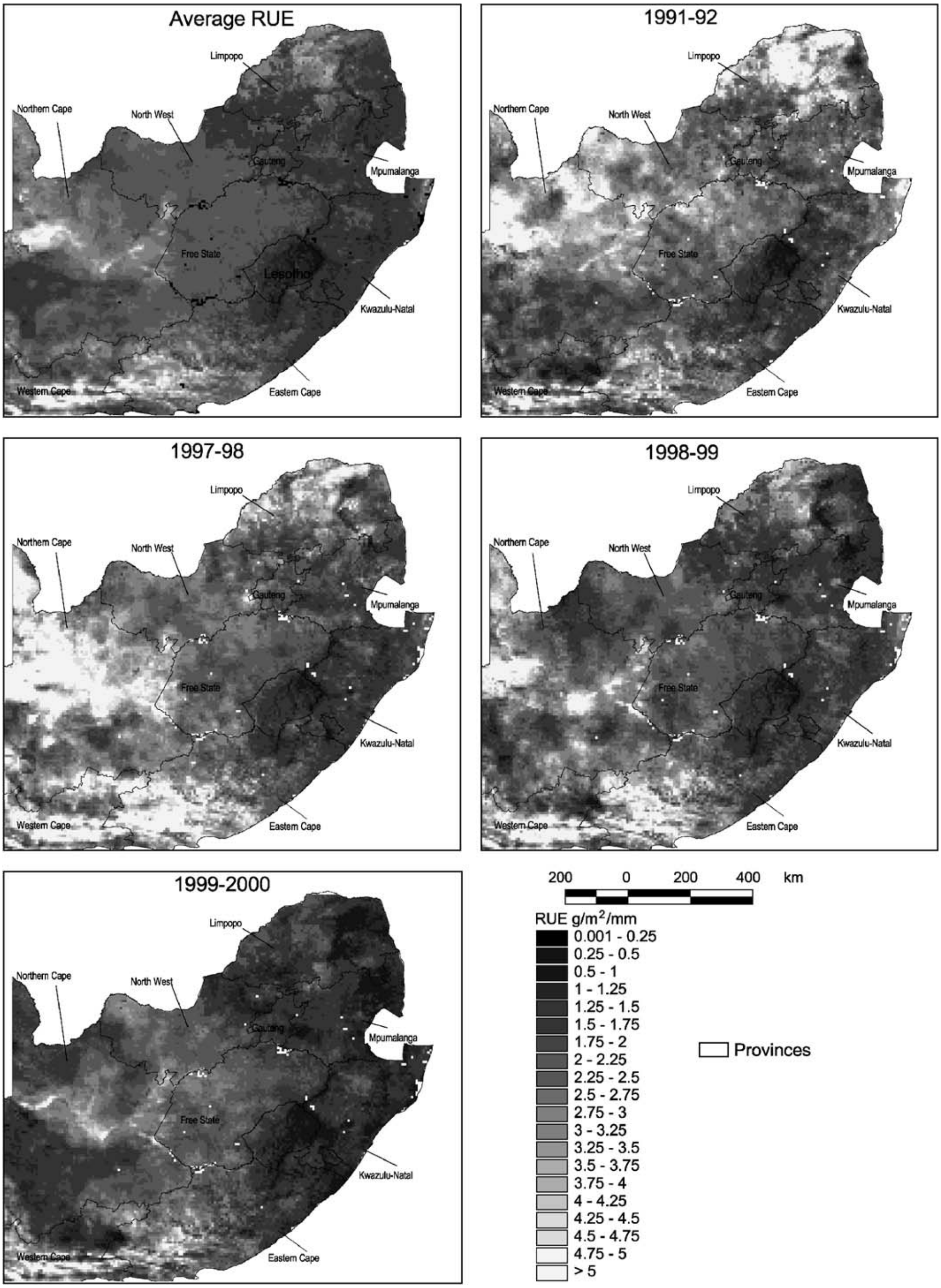


Fig. 5. Average NPP-RUE, 1991–92 NPP-RUE and 1997–98 to 1999–2000 NPP-RUE. Note that the NPP includes both above- and below-ground production.

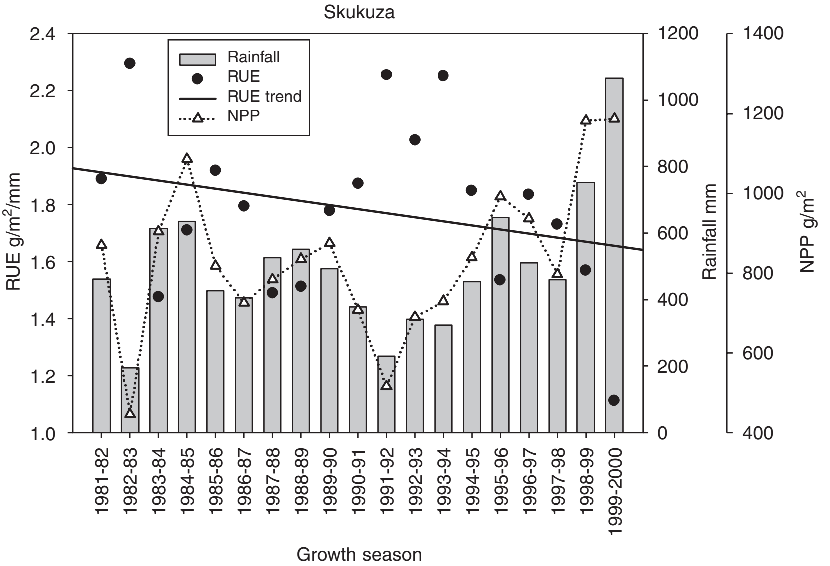


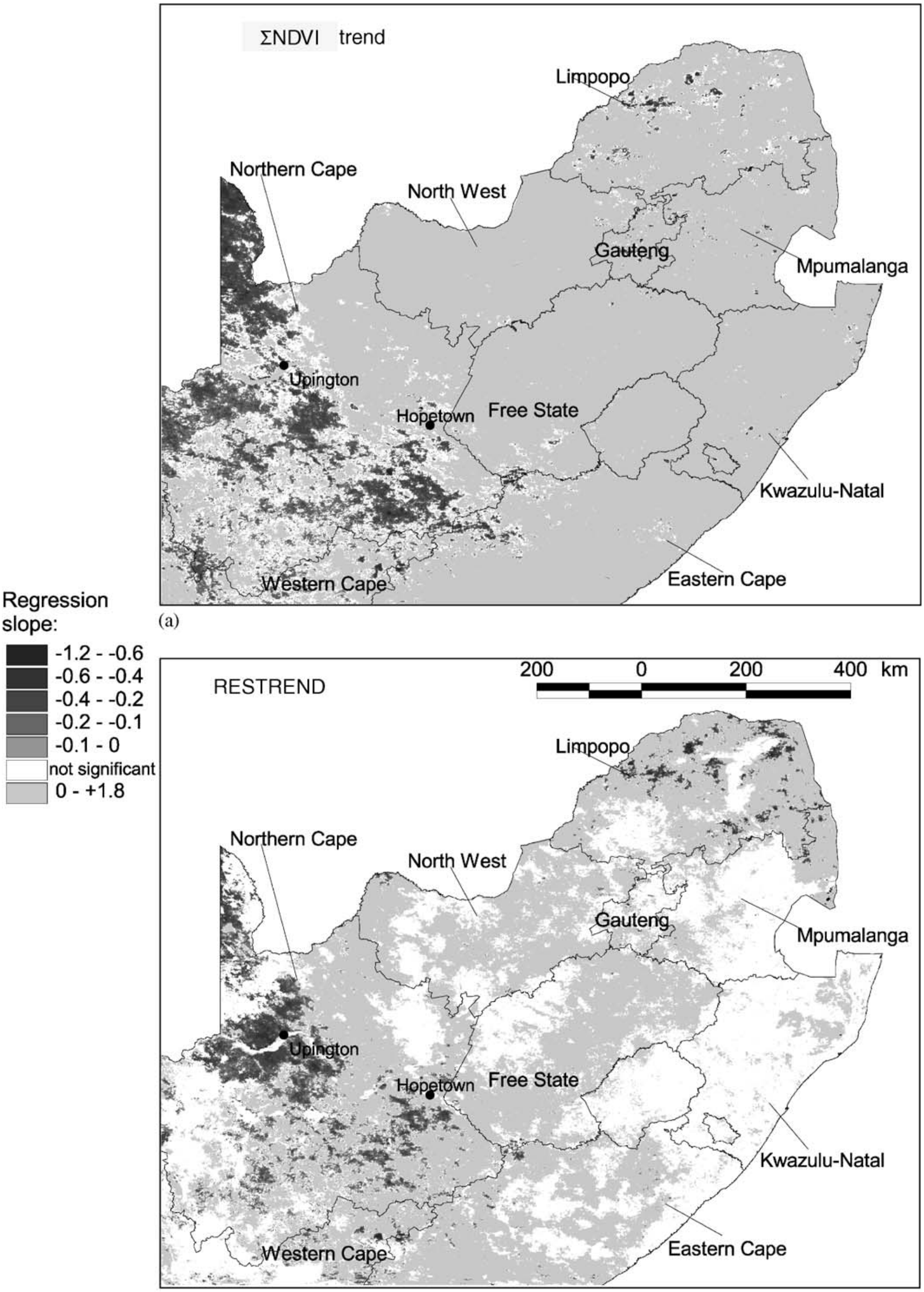
Fig. 6. NPP-RUE profile for Skukuza, Kruger National Park, showing a negative trend as a result of very high rainfall towards the end of the time-series.

Lesotho and the escarpment in the Mpumalanga and Limpopo provinces, probably because although these areas experience high rainfall, there is extensive surface run-off due to steep topography (Fig. 5). Very high average NPP-RUE values were found along the Orange River in the Northern Cape Province probably caused by irrigated cultivation in an otherwise very dry region. The average NPP-RUE was the highest in some of the driest rangelands of SA (<350 mm), i.e. northern Limpopo and northern Northern Cape Provinces (Figs. 1c, 5).

There was considerable inter-annual variation in NPP-RUE as a result of large fluctuations in growth season rainfall (Fig. 5). In 1991–92 and 1997–98, both El Niño years, there were very high NPP-RUE values over parts of the Northern Cape and Limpopo Provinces, which were caused by very low rainfall. In the 1999–2000 La Niña year there were very low NPP-RUE values in the eastern part of the country associated with exceptionally high rainfall.

NPP-RUE was often high in growth seasons with very low rainfall and low NPP (1982–83, 1991–92) and low in growth seasons with high rainfall and high NPP (1998–99, 1999–2000) (e.g. Fig. 6), thus resulting in negative NPP-RUE trends over large areas. The correlation between annual RUE and rainfall was also calculated for each pixel and confirmed a strong negative correlation (average $r = -0.82$, standard deviation $= 0.12$) across the entire SA.

Fig. 7. (a) Map of slope of the ΣNDVI-time regression indicating positive or negative trends. (b) Map of slope of the residual-time regression. The residuals were calculated as the difference between the observed ΣNDVI and predicted ΣNDVI using the linear ΣNDVI–rainfall relationships. Pixels without statistically significant ΣNDVI–rainfall relationships are omitted (white) in (b).


ΣNDVI trend
Limpopo
Northern Cape
North West
Gauteng
Mpumalanga
Upington
Hopetown
Free State
Kwazulu-Natal
Eastern Cape
Western Cape
(a)
Regression slope:
-1.2 - -0.6
-0.6 - -0.4
-0.4 - -0.2
-0.2 - -0.1
-0.1 - 0
not significant
0 - +1.8
RESTREND
200 0 200 400 km
Limpopo
Northern Cape
North West
Gauteng
Mpumalanga
Upington
Hopetown
Free State
Kwazulu-Natal
Eastern Cape
Western Cape
(b)

4.4. *Identifying long-term trends in ΣNDVI*

Most of eastern SA showed a positive trend in ΣNDVI through time, although the Nama Karoo biome (Fig. 1b) and most of the western Northern Cape Province had negative trends (Fig. 7a) (discussed in Section 5). Small areas that had negative trends within areas that otherwise had positive trends may indicate changes in land cover or land condition during the study period (Geerken and Ilaiwi, 2004). Areas in the Gauteng province which had strong negative trends in ΣNDVI (Fig. 7a) appeared to be the result of the expansion of informal settlements (e.g. Hammanskraal), mining operations and urban areas on the outskirts of Pretoria and Johannesburg (Fairbanks et al., 2000). Areas with negative trends in the Mpumalanga Highveld appeared to be associated with coal mining operations and harvesting of forestry plantations.

4.5. *Detecting negative trends in the ΣNDVI–rainfall relationships—RESTREND*

Most of SA showed positive trends of residuals with time and therefore an apparent increase in forage production per unit rainfall (Fig. 7b). There were similarities in the geographic patterns of the residual (Fig. 7b) and the ΣNDVI trends (Fig. 7a). Areas with negative trends in ΣNDVI in the Limpopo Province (Fig. 7a) also had negative residual trends (Fig. 7b). However, more and larger areas had negative residual trends, suggesting that although such areas showed increases in ΣNDVI with time, it was lower than the ΣNDVI predicted by the rainfall. The correlation between annual residuals and rainfall was calculated for each pixel and, in contrast to RUE, the residuals were not correlated with rainfall.

In north-eastern SA the non-degraded areas in seven of the 13 LCUs showed stronger positive residual trends than their paired degraded areas (Table 1). Pixels with negative and positive trends were aggregated when calculating the average values and consequently none of the paired areas ended up with negative average RESTREND values. Where the degraded areas had slightly stronger positive residual trends (LCU 1, 3, 8, 9, 11, 12), these differences were relatively small (Table 1).

A qualitative interpretation of the RESTREND map was conducted in the Limpopo Province (Fig. 8). A number of areas had negative residual trends, for example, the area of commercial rangelands north of the Soutpansberg near the town of Alldays (area 1, Figs. 8 and 9). Areas around the town of Beauty in the former Lebowa homeland had negative residuals in and around areas mapped as degraded by the NLC (area 2, Fig. 8). Parts of the former Venda and Gazankulu homelands along the western boundary of Kruger National Park (KNP) had negative residual trends that might be caused by expanding land degradation, informal settlements, and subsistence cultivation (area 3, Fig. 8). The degraded areas in the Dzanani district (also part of the former Venda homeland) west of Louis Trichardt appeared to be expanding and had negative residual trends (area 4, Fig. 8). Other areas with negative residual trends occurred in the former Lebowa homeland and appeared to be associated with degraded rangelands identified by the NLC (area 5, Fig. 8). A very large area south-east of the town of Baltimore showed negative trends that could be attributed to abandoned agricultural fields, rangeland degradation and expanding informal settlements (area 7, Fig. 8).

Isolated patches within KNP showed negative trends that (area 6, Fig. 8) were caused by negative residuals in the very wet 1999–2000 and the dry 2002–3 growing seasons. Large

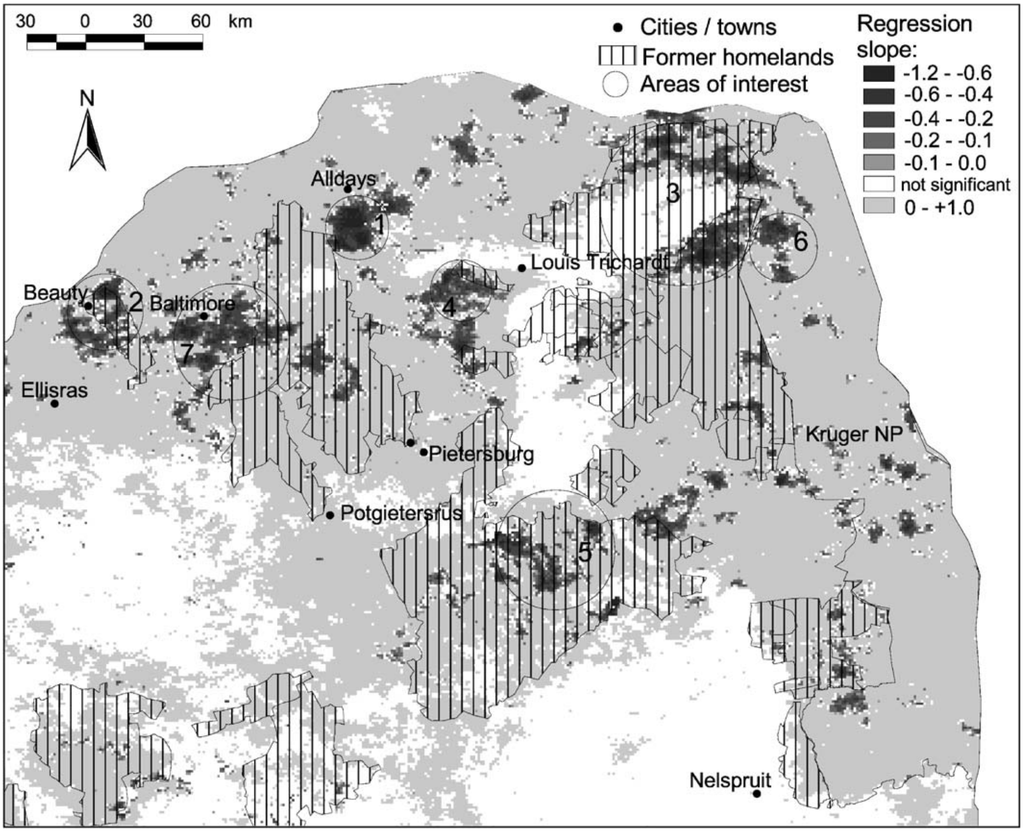


Fig. 8. Enlargement of Fig. 7b for north-eastern SA with former homelands and areas of interest showing negative trends (circles). Map of slope of the residual-time regression. The residuals were calculated as the difference between the observed ΣNDVI and predicted ΣNDVI using the linear ΣNDVI-Log$_e$Rainfall relationships. Pixels without statistically significant relationships are omitted (white).

areas had strong positive residual trends and in an example from KNP (Fig. 8) this positive trend was caused by negative residuals at the beginning of the time-series (1985–88) and large positive residuals in the late nineties (1996–99). The negative residuals at the beginning of the time-series could have been caused by the extended El Niño conditions of the preceding early 1980s.

A large area around the town of Upington in the Northern Cape had negative residual trends (Fig. 7b). Large areas in the Karoo south of Hopetown also showed negative residual trends partly due to very low ΣNDVI values during the 2000–1 and 2002–3 growth seasons. The reasons for these negative trends have not yet been determined.

5. Discussion

The large number of rainfall stations available in SA ($N > 1800$) and the rainfall maps derived from them allowed a comprehensive spatial analysis of the relationship between rainfall and remotely sensed estimates of vegetation productivity. In the past, similar

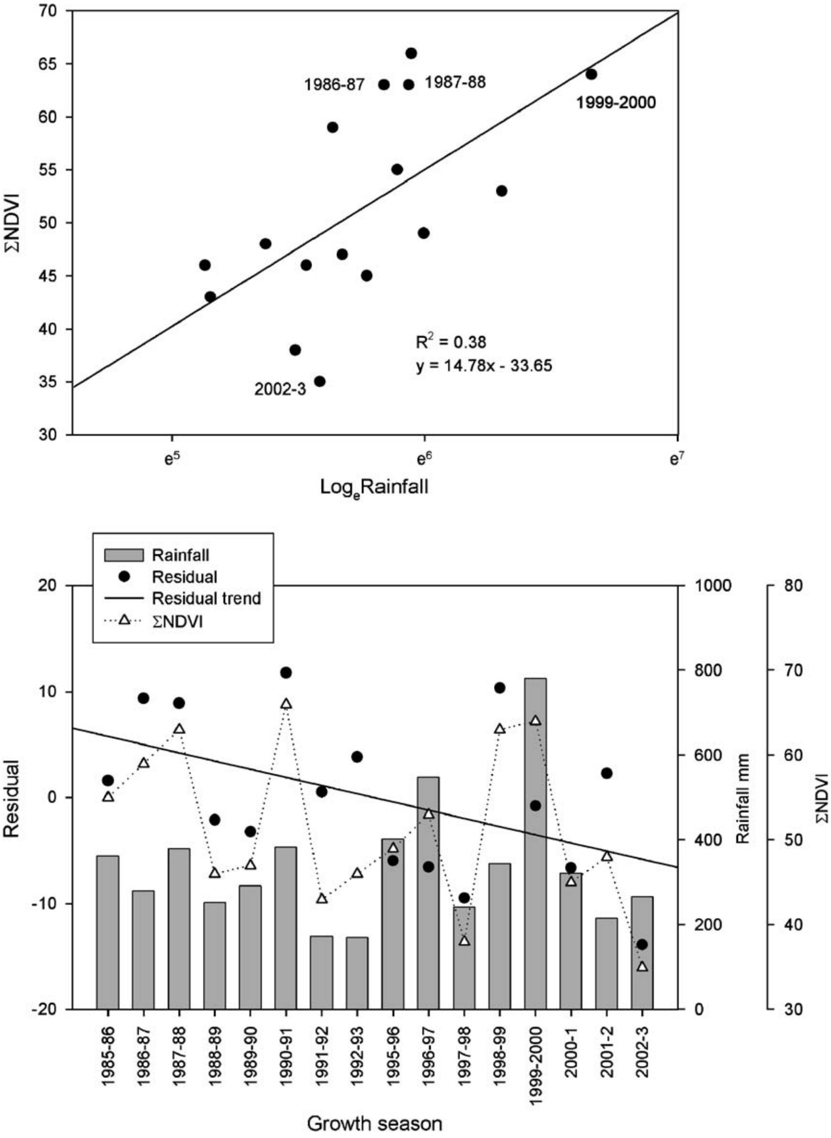


Fig. 9. Linear regression of ΣNDVI and Log$_e$Rainfall (top panel). Trend of residuals plotted against ΣNDVI and rainfall per growth season for a typical pixel in area 1 of Fig. 8 (bottom panel).

studies have been based on point data for 25–200 weather stations (Nicholson and Farrar, 1994; Nicholson et al., 1998; Prince et al., 1998; Diouf and Lambin, 2001). In this study the rainfall–production relationship was derived for every pixel, which effectively accommodated local variations in soils as well as moderate run-off or run-on caused by topography, thus providing a more discriminating and spatially explicit analysis.

The relationships between rainfall and ΣNDVI were comparable to those reported elsewhere (Malo and Nicholson, 1990; Nicholson et al., 1998; Prince et al., 1998; Yang et al., 1998; Diouf and Lambin, 2001). The drier parts of SA (<800 mm mean annual precipitation) had moderate to strong linear relationship between rainfall and both NPP and ΣNDVI (Figs. 3a, b) (Rosenzweig, 1968; Whittaker, 1970; Rutherford, 1980). The NPP–Rainfall relationship was generally stronger than those reported using field data from world-wide semi-arid areas ($R^2 = 0.25-0.4$) (Le Houérou et al., 1988), but Snyman (1998) reported similar values for the Free State, SA.

Areas with high rainfall variability also experienced high variability in vegetation production (Le Houérou, 1984; Le Houérou et al., 1988; Schulze, 1997). In agreement with similar studies (Malo and Nicholson, 1990; Nicholson et al., 1998; Prince et al., 1998; Yang et al., 1998; Diouf and Lambin, 2001) the CV of rainfall was more than double that of NPP in the eastern half of SA. This does not agree with field measurements that suggest 50% greater variation in production than rainfall (Le Houérou et al., 1988; O'Connor et al., 2001; Wiegand et al., 2004). However, the relative variability of phytomass production is highly dependent on the spatial scale and the CV decreases exponentially as the size of plots or pixels increases (Golluscio et al., 2005). Therefore, it appears that the coarse resolution remote sensing estimates of vegetation production may underestimate the temporal variability of production as measured in the smaller field sites (Diouf and Lambin, 2001).

The growth season total rainfall, NPP and NDVI may represent an oversimplification of more complex relationship between water availability and primary production in areas with low R^2 values, since the timing and effectiveness of precipitation have a large influence on vegetation production (Le Houérou, 1984; Justice and Hiernaux, 1986; Tucker et al., 1986; Du Plessis, 1999; Wang et al., 2001; Evans and Geerken, 2004). It is possible that estimates of available soil moisture, that allow for variables such as soil water-holding capacity, run-off, net radiation and actual evapo-transpiration, may give stronger relationships (Farrar et al., 1994). In addition, there may be carryover or lag-effects of extended dry or wet periods on vegetation growth in subsequent growth seasons (Goward and Prince, 1995; Wiegand et al., 2004). However, a previous study in North-eastern SA found no evidence of inter-annual lag-effects between rainfall and ΣNDVI, since conditions regularly alternated from dry to wet between successive years as a result of ENSO events, thus often causing a negative correlation between vegetation production and the rainfall of the previous growth season (Wessels et al., 2004). The rainfall–production models can nevertheless be adapted to account for the potential influence of rainfall of previous growth seasons. Overall, the current results clearly indicate that rainfall has a major influence on the vegetation production in SA and therefore may mask the often lesser effects of human-induced land degradation.

The ΣNDVI-RUE of most of the degraded areas in north-eastern SA were consistently lower than paired non-degraded areas (Fig. 4), thus confirming that degraded areas produced less forage per unit rainfall received in any given growth season (Wessels et al., 2004). This also agrees with field experiments which compared degraded and non-degraded sites in SA (Snyman, 1998; Illius and O'Connor, 1999; O'Connor et al., 2001). As in field observations (O'Connor et al., 2001), the lowest ΣNDVI-RUE and NPP-RUE values occurred in the wettest growth seasons (e.g. 1999–2000) (Figs. 4–6). The RUE values varied considerably from year to year, associated with varying rainfall (Fig. 4). In contrast, Nicholson et al. (1998) reported that the NDVI-RUE showed little inter-annual variability during a 13-year period in the Sahel. However, their calculation was based on the average of all the weather stations ($N = 141$), thus obscuring site-specific, inter-annual variation in RUE and precluding the use of RUE for spatial monitoring.

RUE showed very large inter-annual variations as a result of a strong negative correlation with rainfall (country-wide average $r = -0.82$) (Figs. 4–6). The RUE trend map showed negative trends where very high rainfall towards the end of the time-series caused low RUE values despite exceptionally high NPP values (1998–99 and 1999–2000, Figs. 5 and 6). It is clear that simply calculating the annual ratio of NPP or ΣNDVI and rainfall does not remove the effects of rainfall variability on vegetation production for individual years and that inter-annual comparisons of RUE maps cannot be used to monitor land degradation as suggested elsewhere (Holm et al., 2003; Symeonakis and Drake, 2004). Dividing the less variable NPP or ΣNDVI by the highly variable rainfall can not be expected to produce an index which is independent of rainfall.

By accounting for rainfall, the RESTREND method identified areas with negative residual trends (Fig. 7b) which actually had positive ΣNDVI trends (Fig. 7a). These areas had lower ΣNDVI values than predicted by the rainfall–ΣNDVI relationship and therefore may have experienced a reduction in production per unit rainfall. At a national scale it is very difficult to verify if areas showing negative residual trends were indeed being degraded during the time-series, since there has never been a country-wide rangeland monitoring program in SA. The NRLD (Hoffman et al., 1999; Hoffman and Ashwell, 2001) does however, provide information on the perceived rate of change in rangeland condition of magisterial districts over a 10 year period (1989–1999), as judged by local experts (Fig. 10). Although it was difficult to compare the rating of an entire district to the trends in distinct locations, similar patterns were evident. Many of the former homeland districts in the Limpopo Province that were judged to have experienced increased rates of land degradation since 1989, showed negative trends in residuals (Figs. 8 and 10). In agreement

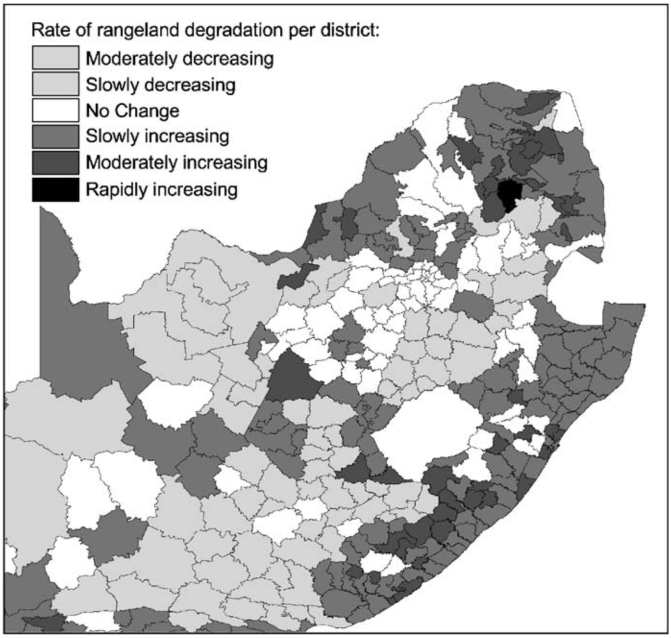


Fig. 10. Rate of rangeland degradation per district between 1989 and 1999, as judged by experts, after Hoffman et al. (1999).

with the slowly increasing rate of degradation reported for some Northern Cape and Karoo districts (Hoffman et al., 1999), the ΣNDVI trend and residuals trend maps also indicated reductions in vegetation productivity in these general areas (Figs. 7a, b). These results may be relevant to the long-debated question of whether the semi-arid Karoo is expanding (Acocks, 1953; Dean et al., 1995; Archer, 2004).

The RESTREND method also showed promising results in the Limpopo Province, where negative trends were associated with degraded areas mapped by the NLC in and around communal areas (Fig. 8). However not all degraded areas had negative residual trends (Table 1), since the communal homelands were created as long ago as 1913–1936

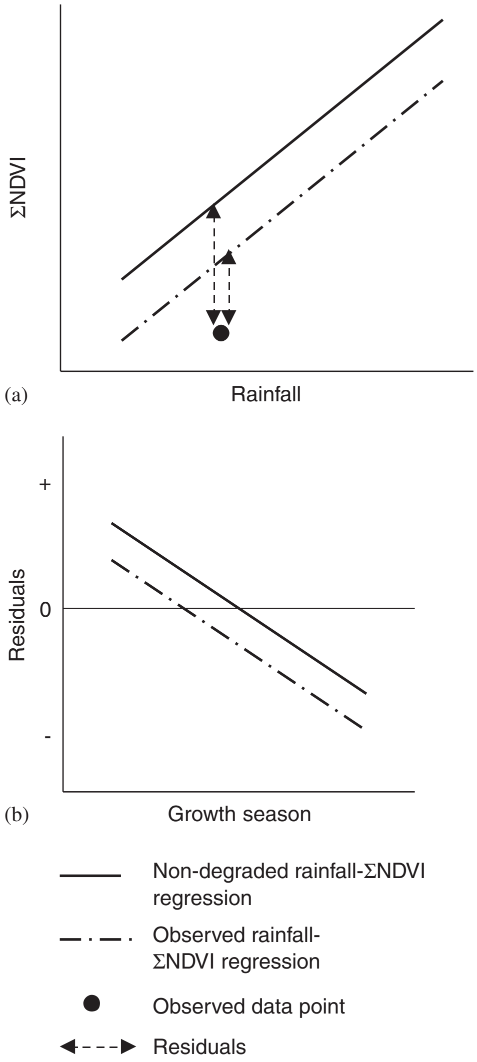


Fig. 11. (a) Potential effects of degradation on the observed rainfall–ΣNDVI relationships (OR) in comparison with the non-degraded rainfall–ΣNDVI relationships (NR) and (b) trends in the residuals with respect to time.

(Christopher, 1994) and much of the land degradation in these areas probably occurred before the start of the satellite record (1981–85). These areas may therefore have experienced slight improvements in condition and some positive residual trends (Table 1), although they are today still regarded as degraded.

The RESTREND method has some potential weaknesses. First, since a non-degraded reference period does not exist, both the underlying rainfall–production relationship and degradation impacts have to be extracted from the same time-series. Since the time-series include unknown degrees of degradation, the observed rainfall–production relationships may be quite different from an underlying, non-degraded relationship. If there has been degradation, the observed relationship will generally underestimate the production expected for a given amount of rainfall (Fig. 11a) and, as a result, the residuals will underestimate the magnitude of degradation (Fig. 11b). However, as long as the degradation causes a fixed reduction in production, independent of rainfall (Fig. 11a), the calculated slope of the residuals with respect to time is not affected (Fig. 11b) (Evans and Geerken, 2004). Second, the trend in the residuals is affected by the point in the time-series when the degradation takes place. Simulations showed that a fixed 15% reduction in ΣNDVI starting in the middle of the time-series will result in the most negative slope, while the same reduction applied near the beginning or end of the time-series results in less negative trends in residuals (Fig. 12). Degradation occurring within the first or last 2 years of the time-series would be very difficult to detect. However, this problem is common to all trend analyses that are based on a limited time-series. The trend of the residuals through time is therefore influenced by both the timing and the magnitude of the degradation. Third, like all remote sensing-based change detection methods, the RESTREND method can only detect degradation impacts that occurred during the satellite time-series and does not provide a map of all historical degraded land. This complicates comparisons with other static maps of degradation (e.g. NLC) that include all degradation impacts, without any indication of when they occurred. The RESTREND method may furthermore be

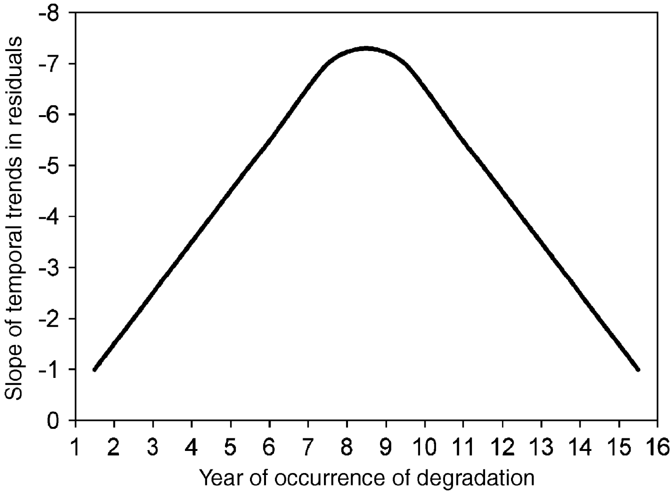


Fig. 12. Effect of timing of the occurrence of degradation on the slope of temporal trends of residuals. Simulations were based on a fixed 15% reduction in ΣNDVI starting in each of the 16 years in the time-series.

improved by using multiple regression to account for the carryover effects of rainfall of previous growth seasons (Wiegand et al., 2004) and may benefit from non-parametric trend analyses (Hirsch and Slack, 1984; DeBeurs and Henebry, 2004).

6. Conclusions

Although degraded areas in north-eastern SA had reduced ΣNDVI-RUE, RUE has a strong negative correlation with rainfall and annual RUE maps can not be compared to monitor land degradation. The results suggest that the RESTREND method is a useful tool for controlling the effects of rainfall in order to detect human-induced land degradation. Examples from KNP showed that both negative and positive residual trends could result from natural ecological processes. Major land use and land cover changes, such as the expansion of subsistence agriculture, can also result in negative trends. The RESTREND method can evidently only identify areas where there has been a reduction in production per unit rainfall, but the exact cause of the negative trend, e.g. overgrazing by livestock, can not be determined by this method alone. It is therefore envisaged that the RESTREND method would ultimately form part of a multi-scale, monitoring system where it can serve as a regional indicator to identify potentially degraded areas which can then be closer investigated using high-resolution remote sensing data and field work. Field surveys will remain an essential part of such a monitoring program, since they provide validation data for the remote sensing products and can track aspects of land degradation such as, vegetation species change and soil erosion, that are not necessarily detectable with satellite data. The SA National Department of Agriculture (DoA, Directorate: Land use and Soil Management) is therefore currently planning an extensive field campaign to start monitoring 2000 fixed sites throughout the country.

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