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Land Degradation and Improvement in South Africa
1. Identification by remote sensing

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World Soil Information

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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MAIN POINTS

1. **Land degradation is a global environment and development issue.** Up-to-date, quantitative information is needed to support policy and action for food and water security, economic development, environmental integrity and resource conservation. To meet this need, the Global Assessment of Land Degradation and Improvement uses remote sensing to identify degrading areas and areas where degradation has been arrested or reversed. In the LADA partner countries, this screening will be followed up by field investigations to establish the situation on the ground.
2. **Land degradation is defined as a long-term decline in ecosystem function and measured in terms of net primary productivity.** The remotely-sensed normalised difference vegetation index (NDVI) is used as a proxy; land degradation and improvement is inferred from long-term trends when other factors that may be responsible (climate, soil, terrain and land use) are accounted for. Rainfall effects may be accounted for by rain-use efficiency (NDVI per unit of rainfall) and residual trends of NDVI; temperature effects may be accounted for by energy-use efficiency (derived from accumulated temperature). Spatial patterns and trends of NDVI combined with climatic indices are analysed for the period 1981-2003 at 8km resolution; land degradation is indicated by a declining trend of climate-adjusted NDVI and land improvement by an increasing trend.
3. **In South Africa, net primary productivity decreased over the period 1981-2003 against a background of a population increase of 50 per cent** (from 30 millions to 45 millions). Areas of decreasing climate-adjusted NPP occupy some thirty per cent of the country, mostly in the north-east.
4. **Twenty-nine per cent of the degrading area, so defined, is cropland – 41 per cent of all cultivated areas**; 33 per cent is forest (55 per cent of the forest area); and 37 per cent rangeland. Overall, these areas suffered an average loss of NPP of 29 kg C/ha/year. There is no obvious relationship between degrading land and soil or terrain, and only a weak correlation with aridity: 37 per cent of degrading areas are in humid regions, 20 per cent in dry sub-humid, 31 per cent in semi-arid, and 12 per cent in arid and hyper-arid regions.
5. **About 17 million people (38 per cent of the population) live in the degrading areas.** There is a weak correlation between degrading land and rural population density; degradation is somewhat over-represented in the communal lands but not overwhelmingly; more detailed analysis of land use history is needed to tease out the underlying social and economic drivers.
6. **One third of the country shows an increase in climate-adjusted net primary productivity.** Most of these areas are in the west of the country; 84 per cent is rangeland, 9 per cent cropland and 7 per cent forest.

Key words: land degradation/improvement, remote sensing, NDVI, rain-use efficiency, net primary productivity, land use/cover, South Africa

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Abbreviations

CIAT	International Centre for Tropical Agriculture, Cali, Columbia
CIESIN	Center for International Earth Science Information Network, Colombia University, Palisades, NY
CoV	Coefficient of Variation
CRU TS	Climate Research Unit, University of East Anglia, Time Series
ENSO	El Niño/Southern Oscillation
FAO	Food and Agriculture Organization of the United Nations, Rome
GEF	The Global Environment Facility, Washington DC
GIMMS	Global Inventory Modelling and Mapping Studies, University of Maryland
GLADA	Global Assessment of Land Degradation and Improvement
GLASOD	Global Assessment of Human-Induced Soil Degradation
GPCC	The Global Precipitation Climatology Centre, German Meteorological Service, Offenbach
JRC	European Commission Joint Research Centre, Ispra, Italy
LADA	Land Degradation Assessment in Drylands
Landsat ETM+	Land Resources Satellite, Enhanced Thematic Mapper
LUS	Land Use Systems, FAO
MOD17A3	MODIS 8-Day Net Primary Productivity data set
MODIS	Moderate-Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NPP	Net Primary Productivity
RESTREND	Residual Trend of sum NDVI
RUE	Rain-Use Efficiency
SOTER	Soil and Terrain database
SOTERSAF	Soil and Terrain database of Southern Africa
SPOT	Système Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme, Nairobi
VASClimO	Variability Analyses of Surface Climate Observations

1 Introduction

Ever-more-pressing demands on the land from economic development, burgeoning cities and growing rural populations are driving unprecedented land-use change. In turn, unsustainable land use is driving land degradation: a long-term loss in ecosystem function and productivity that requires progressively greater inputs to repair the situation. Its symptoms include soil erosion, nutrient depletion, salinity, water scarcity, pollution, disruption of biological cycles, and loss of biodiversity. This is a global development and environment issue - recognised by the UN Convention to Combat Desertification, the Conventions on Biodiversity and Climatic Change, and Millennium Goals (UNCED 1992, UNEP 2007).

Quantitative, up-to-date information is needed to support policy development for food and water security, environmental integrity, and economic development. The only previous harmonized assessment of land degradation, the *Global assessment of human-induced soil degradation* (Oldeman and others 1991), is a map of perceptions (the kinds and degree of degradation) not a measure of degradation, and is now out of date. Within the FAO program *Land Degradation Assessment in Drylands (LADA),* the present *Global Assessment of Land Degradation and Improvement (GLADA)* maps *hot spots* of land degradation and *bright spots* of land improvement according to change in net primary productivity (NPP, the rate of removal of carbon dioxide from the atmosphere and its conversion to biomass). In the next phase of the program, hot spots and bright spots will be further characterised in the field by national teams.

Satellite measurements of the normalised difference vegetation index (NDVI or greenness index) for the period 1981-2003 are used as a proxy for NPP. NDVI data have been widely used in studies of land degradation from the field scale to the global scale (e.g. Tucker and others 1991, Bastin and others 1995, Stoms and Hargrove 2000, Wessels and others 2004, 2007, Singh and others 2006). However, remote sensing can provide only indicators of land degradation and improvement: a negative trend in greenness does not necessarily mean land degradation, nor does a positive trend necessarily mean land improvement. Greenness depends on several factors including climate (especially fluctuations in rainfall, temperature, sunshine and length of the growing season), land use and management; changes may be interpreted as land degradation or improvement only when these other factors are accounted for.

Where productivity is limited by rainfall, rain-use efficiency (RUE, the ratio of NPP to rainfall) accounts for variability of rainfall and, to some extent, local soil characteristics. RUE is strongly correlated with rainfall; in the short term, it says more about rainfall fluctuation than land degradation but we judge that its long-term trends distinguish between rainfall variability and land degradation. To get around the correlation of RUE with rainfall, Wessels and others (2007) have suggested the alternative use of residual trends of NDVI (RESTREND) – the difference between the observed NDVI and that modelled from the local rainfall-NDVI relationship.

In this report, land degradation is identified by a declining trend in *both* NDVI and RUE, presented as RUE-adjusted NDVI, which may be translated to NPP values that

are open to economic analysis. This translation is approximate. Comparable RESTREND values are presented as an additional layer of information. The pattern of land degradation is further explored by comparisons with soil and terrain, land cover, and socio-economic data.

2 Context and methods

2.1 GLADA partner country: South Africa

In South Africa, land degradation is severe and widespread. It threatens food and water security, economic development, and natural resource conservation. Hoffman and others (1999) summarized the severity, extent and rates of different types of land degradation within the 367 magisterial districts based on qualitative assessments by natural resource conservation officers. The former *homelands,* now called communal lands, are a major concern (Hoffman and Todd 2000, Hoffman and Ashwell 2001); they are characterized by high human and livestock populations, overgrazing, soil erosion, excessive wood harvesting and the loss of palatable pasture species (Shackleton and others 2001). This is commonly attributed to a combination of poverty and failure of regulation (Hoffman and Todd 2000, Scholes and Biggs 2004) arising from both current socio-economic changes and a legacy from the previous apartheid regime (Dean and others 1996, Fox and Rowntree 2001, McCusker and Ramudzuli 2007). There is concern that current land redistribution programs might expose productive land to the same drivers of degradation. However, degradation also occurs in commercially-farmed land - and not all communal lands are degraded.

Degraded lands have been mapped as part of the National Land Cover map using expert interpretation of 1995-6 Landsat imagery (Fairbanks and others 2000); some 5 per cent of the country (5.8 million ha) was mapped as degraded. Using 18 years of 1km-resolution NDVI data, Wessels and others (2004, 2007) found that production on degraded rangeland is about 20 per cent lower than on adjacent non-degraded lands with comparable soils and climate.

2.2 Data

2.2.1 NDVI and net primary productivity

The NDVI data used in this study are produced by the Global Inventory Modelling and Mapping Studies (GIMMS) group from measurements made by the AVHRR radiometer on board US National Oceanic and Atmospheric Administration satellites. The fortnightly images at 8km-spatial resolution are corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation cover (Tucker and others 2004). These data are compatible with those from other sensors such as MODIS, SPOT Vegetation, and Landsat ETM+ (Tucker and others 2005, Brown and others 2006). GIMMS data from July 1981 to December 2003 were used for this study.

To get a measure of land degradation and improvement that is open to economic analysis, the GIMMS NDVI time series has been translated to NPP using MODIS (moderate-resolution imaging spectro-radiometer) data for the overlapping period 2000-2003. MOD17A3 is a dataset of terrestrial gross and net primary productivity, computed at 1-km resolution at an 8-day interval (Heinsch and others 2003,

Running and others 2004). Though far from perfect (Plummer 2006), MODIS has been validated in various landscapes (Fensholt and others 2004, 2006, Gebremichael and Barros 2006, Turner and others 2003, 2006); MODIS gross and net primary productivity are related to observed atmospheric CO_2 and the inter-annual variability associated with the ENSO phenomenon, indicating that the NPP data are reliable at the regional scale (Zhao and others 2005, 2006).

2.2.2 Climatic data

The VASClimO 1.1 dataset is compiled from long, quality-controlled station records, gridded at resolution of 0.5°, from 9 343 stations (Beck and others 2005), about 60 in South Africa; these are the most complete precipitation data for 1951-2000. For the period up to 2003, they have been supplemented by the GPCC full data re-analysis product (Schneider and others 2008) to provide monthly rainfall to match the GIMMS NDVI data. Mean annual temperature values from the CRU TS 2.1 dataset (Mitchell and Jones 2005) of monthly station-observed values, also gridded at 0.5^{o} resolution, were used to calculate the aridity index and energy-use efficiency.

2.2.3 Soil and terrain

A dataset of key soil and terrain attributes has been prepared for GLADA using the 90m-resolution SRTM digital elevation model and the 1:1 million-scale SOTERSAF database (Batjes 2004, FAO/ISRIC 2003).

2.2.4 Land cover and land use

In lieu of a digital version of the *National land cover map of South Africa*, *Land Cover 2000* global land cover data (JRC 2003) have been generalised for South Africa (Figure 1) and used for preliminary comparison with NPP trends. Likewise, land use data for South Africa have been derived from *Land use systems of the World* (FAO 2008).

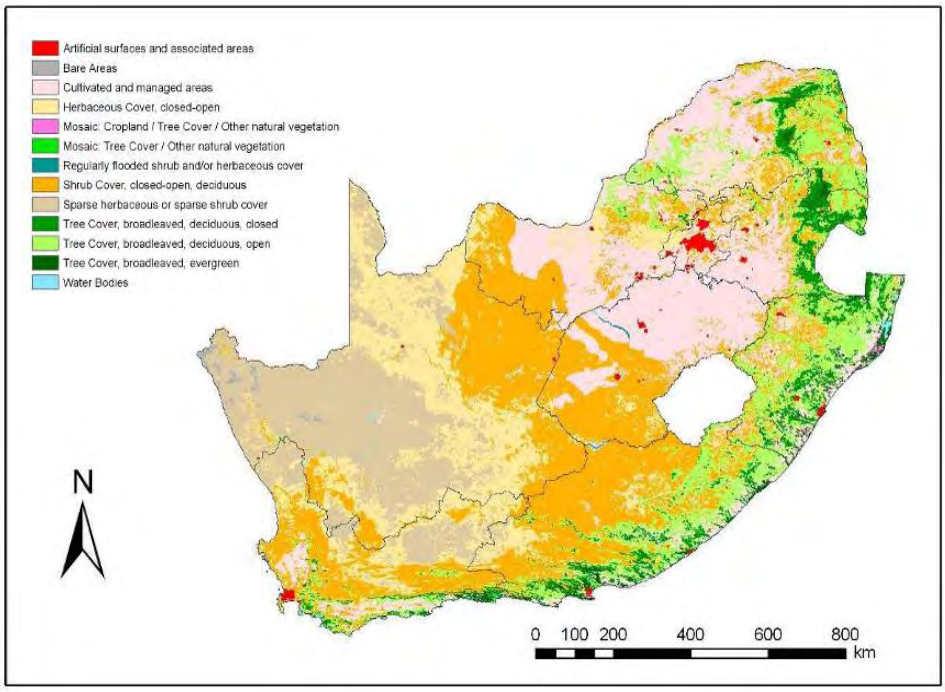


Figure 1. Main land cover types
(JRC 2003)

2.2.5 Population, urban areas and poverty indices

The CIESIN Global Rural-Urban Mapping Project provides data for population and urban extent, gridded at 30 arc-second resolution (CIESIN 2004). For this study, the Urban/Rural Extents dataset is used to delineate the urban area. Sub-national rates of infant mortality and child underweight status at 2.5 arc-minutes resolution have been used as proxies for poverty (CIESIN 2005) for comparison with indicators of land degradation.

2.2.6 Aridity index

Turc's aridity index was calculated as P/PET where P is annual precipitation in mm and $PET = P/\sqrt{(0.9+(P/L)^2)}$ where L = 300 + 25T + 0.05T^3 where T is mean annual temperature (Jones 1997). Precipitation was taken from the gridded VASClimO data, mean annual temperature from the CRU TS 2.1 data.

2.2.7 RESTREND

Following the general procedure of Wessels and others (2007), correlations were calculated between annual sum NDVI and annual rainfall (beginning October 1 through the following September) for each pixel. The regression equation enables prediction of sum NDVI according to rainfall. Residuals of sum NDVI (i.e. differences between the observed and predicted sum NDVI) were calculated, and the trend of these residuals was analysed by linear regression.

2.3 Analysis

Areas of land degradation and improvement are identified by a sequence of analyses of remotely sensed data:

1. Simple NDVI indicators: NDVI minimum, maximum, maximum-minimum, mean, sum, standard deviation and coefficient of variation are computed for the period October through the following September, encompassing a complete growing season. Their trends are analysed over the 23-yearperiod of the GIMMS data (Appendix 2).
2. Annual sum NDVI, representing the aggregate of greenness over the biological year, is chosen as the standard proxy for annual biomass productivity. NDVI is translated to net primary productivity (NPP) by correlation with MODIS data; trends are calculated by linear regression.
3. To distinguish between declining productivity caused by land degradation, and declining productivity caused by rainfall variability, the following procedure was adopted:
    a. Identify the areas where there is a positive relationship between productivity and rainfall, i.e. where rainfall determines NPP;
    b. For those areas where rainfall determines productivity, RUE is considered: where productivity declined but RUE increased, declining productivity was attributed to declining rainfall and those areas were masked;
    c. For the remaining areas with a positive relationship but declining RUE, and also for areas where there is a negative relationship between NDVI and rainfall, i.e. humid and irrigated areas where rainfall does not determine NPP, NDVI trend has been calculated; this is called *RUE-adjusted NDVI*;
    d. Land degradation is indicated by a negative trend in RUE-adjusted NDVI and may be quantified as RUE-adjusted NPP.
4. Residual trends of NDVI (RESTREND)
5. Energy-use efficiency – ratio between annual sum NDVI and accumulated temperature;
6. Stratification of the landscape according to land use, soil and terrain, aridity index and calculate the loss of NPP, e.g. for all land use types or degrading areas; urban areas are masked;
7. Comparison of indices of land degradation with factors such as rural population density and poverty.

Details of the analytical methods are given as Appendix 1. Algorithms have been developed that enable these screening analyses to be undertaken automatically.

At the next stage of analysis, the degrading and improving areas identified on the basis of NDVI indices will be characterised manually, using 30m-resolution Landsat data, to identify the probable kinds of land degradation. At the same time, the continuous field of the index of land degradation derived from NDVI and climatic data will enable a statistical examination of other data for which continuous spatial

coverage is not available, for instance spot measurements of soil attributes, and other social and economic data that may reflect the drivers of land degradation, provided that these other data are geo-located.

Finally, field examination of the identified areas of degradation and improvement will be undertaken by national teams within the LADA program.

3 Results

The spatial patterns and temporal trends of various indicators of land degradation and improvement are presented in Appendix 2. The main text deals with interpretation of the annual sum NDVI data which are taken to represent annual green biomass production.

3.1 Trends in biomass productivity

Biomass productivity fluctuates in concert with rainfall. Countrywide, greenness decreased slightly over the period 1981-2003 (Appendix 2, Table A1), compared with an overall global increase of 3.8 per cent and an increase of 3 per cent for Africa as a whole (Bai and others 2008). Figure 2, shows the country average tracking the ENSO cycle with losses during El Niño events and gains during La Nina events. However, there are significant regional differences.

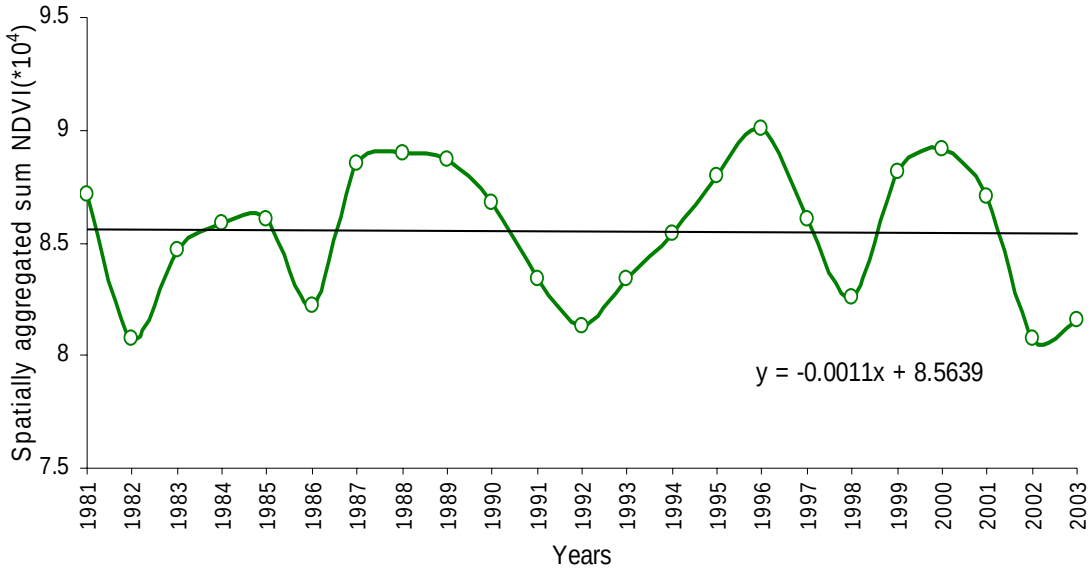


Figure 2. Spatially aggregated annual sum NDVI 1981-2003, $p<0.01$
(The year begins 1 October and continues through the following September)

Figure 3 depicts 23-year mean annual sum NDVI and trends over the period 1981-2003, determined for each pixel by the slope of the linear regression equation. The annual sum NDVI increased across 55 per cent of the country, mostly in the west, and decreased over 45 per cent of the country, mostly in the east.

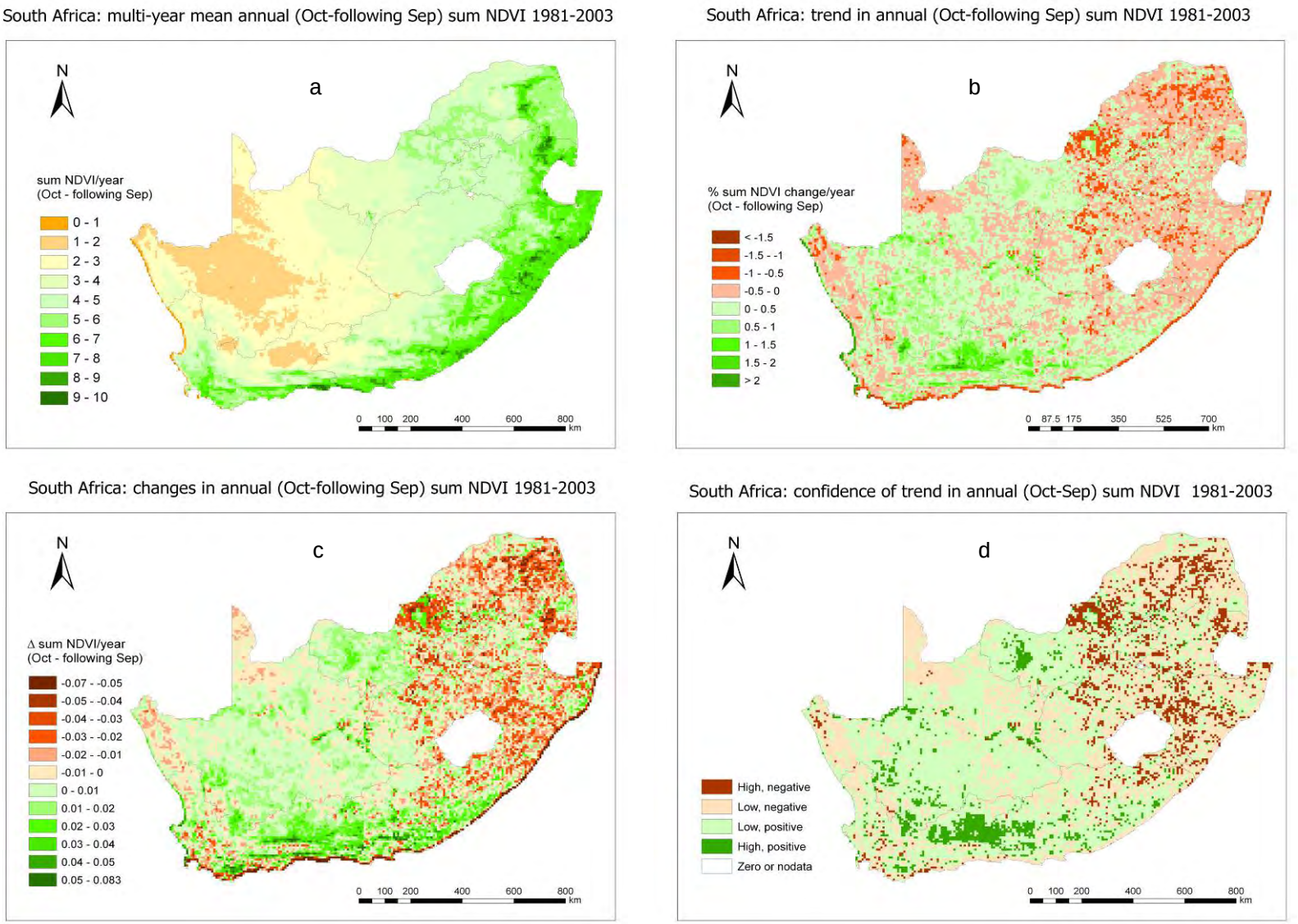


Figure 3. Annual sum NDVI 1981-2003 Pattern (a), trends (b – percentage, c - absolute) and confidence levels (d)

3.2 Spatial patterns of biomass and rainfall

Biomass fluctuates according to rainfall, season and stage of growth, and changes in land use, as well as according to land quality. Across South Africa, biomass productivity (represented by sum NDVI in Figure 3a) essentially follows rainfall (Figure 5a) which is very variable both spatially (Figure 5b, c) and cyclically (Figure 4, Figure 6). Statistics show a high correlation between NDVI and annual rainfall at the pixel level:

$$NDVI_{ann.\ sum} = 0.0066 * \text{Rainfall [mm yr}^{-1}\text{]} + 1.167 \quad (r^2 = 0.72,\ n = 21\,066) \quad [1]$$

The error or uncertainty in the regression model [1] is: slope (0.0066) ± 0.000055. This is very small; the model is reliable.

The coefficient of variation (r^2) indicates that 72 per cent of the variation in biomass productivity is explained by variation in rainfall. Over the study period, rainfall increased across three quarters of the country (east Kwazulu-Natal, Mpumalanga, Gauteng and north-central Northern Cape), with an average rate of 3mm/yr, and decreased across one quarter, at 1.7mm/yr (Figure 5b and c). However, while rainfall increased over the country as a whole (Figure 6), biomass productivity actually decreased slightly (Figure 2).

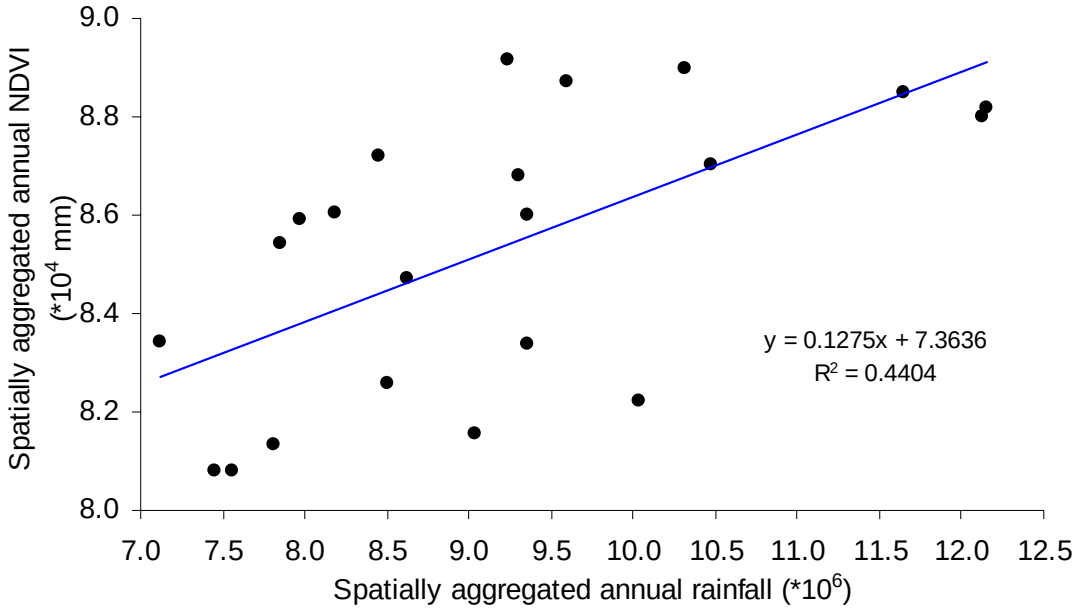


Figure 4. Relationship between annual sum NDVI and annual rainfall (all pixels)
The year begins 1 October and continues through the following September, each dot represents one year, $p < 0.001$

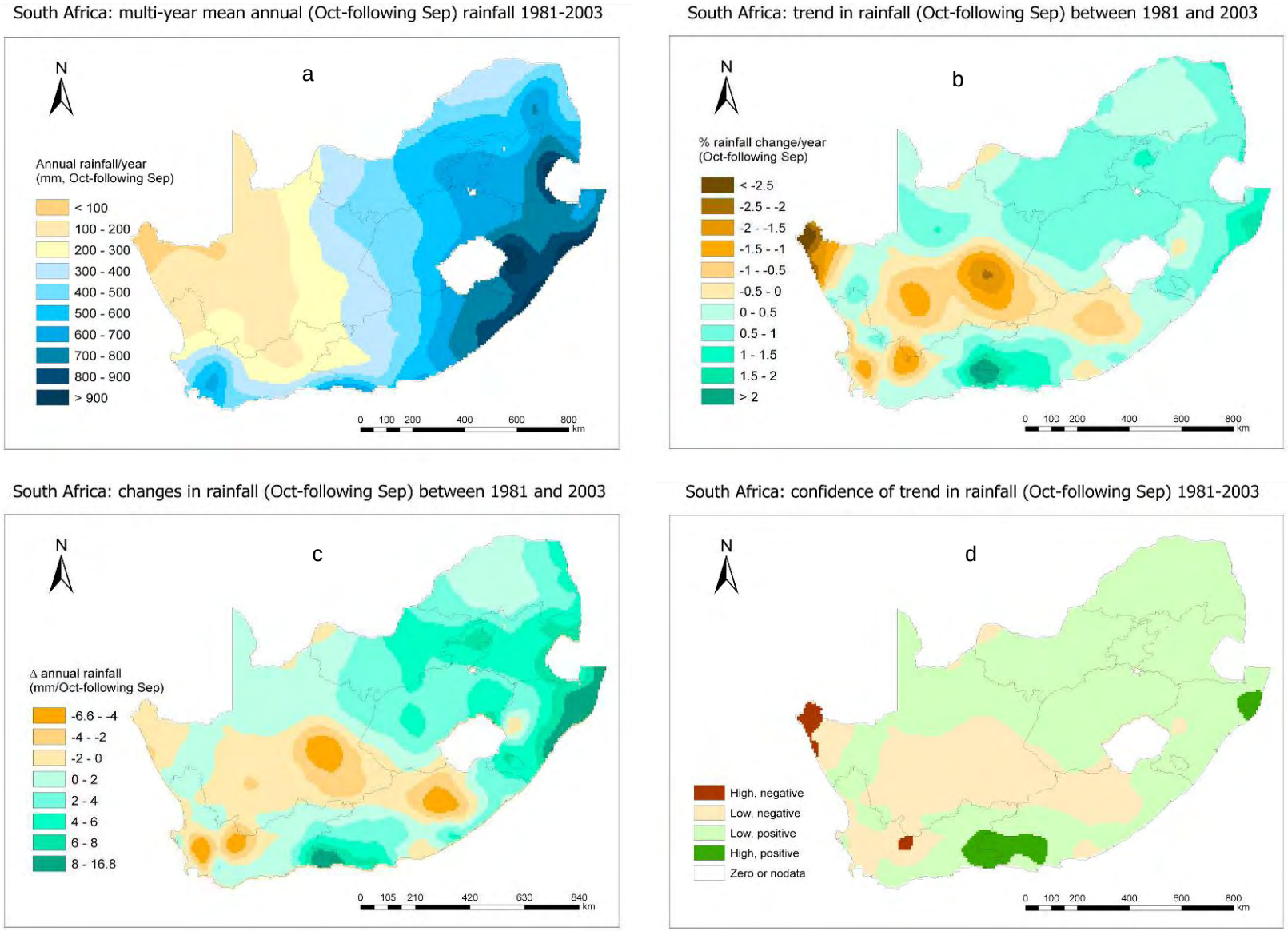


Figure 5. Annual rainfall 1981-2003 Spatial pattern (a), temporal trends (b – percentage change, c – absolute change), confidence levels (d)

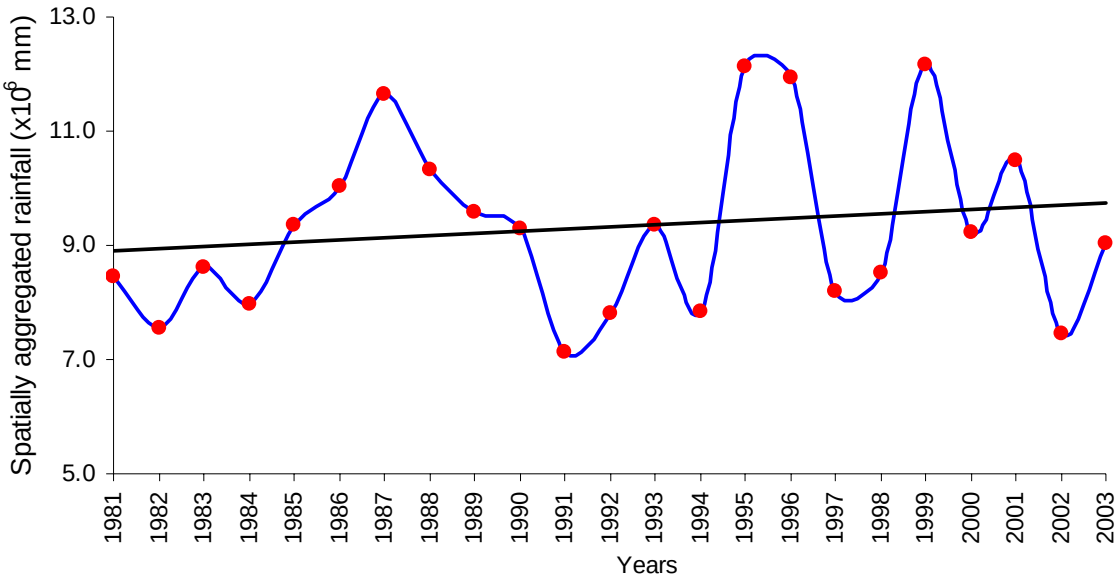


Figure 6. Spatially aggregated annual rainfall 1981-2003, *p<0.01*
The year begins 1 October and continues through the following September

3.3 Rain-use efficiency

The effects of fluctuations in rainfall on biomass productivity may be taken into account by considering rain-use efficiency (RUE), i.e. production per unit of rainfall. RUE may fluctuate wildly in the short term - often, there is a sharp decline in RUE in a wet year and we may assume that the vegetation, whether cultivated or semi-natural, cannot make use of the additional rain. However, where rainfall is the main limiting factor on biomass productivity, we judge that the long-term trend of RUE is a good indicator of land degradation or improvement (Houérou 1984, 1988, 1989; Snyman 1998; Illius and O'Connor 1999; O'Connor and others 2001). Analysis of the local rainfall–biomass relationship also accommodates the effects of local variations in slope, soil and vegetation (Justice and others 1991).

In North China and Kenya, Bai and others (2005, 2006) demonstrated that values for RUE calculated from NDVI, which are easy to obtain, were comparable with those calculated from field measurements of NPP, which are not easy to obtain. For South Africa, RUE was calculated as the ratio between annual sum NDVI and station-observed annual rainfall.

Figure 7 maps mean annual RUE and its trend over the period 1981-2003: RUE is generally higher in the drylands than the humid areas which generate drainage to streams and groundwater (Figure 7a); over the period 1981-2003, RUE decreased over 55 per cent of the country and increased over 45 per cent. Confidence levels are assessed by the T-test.

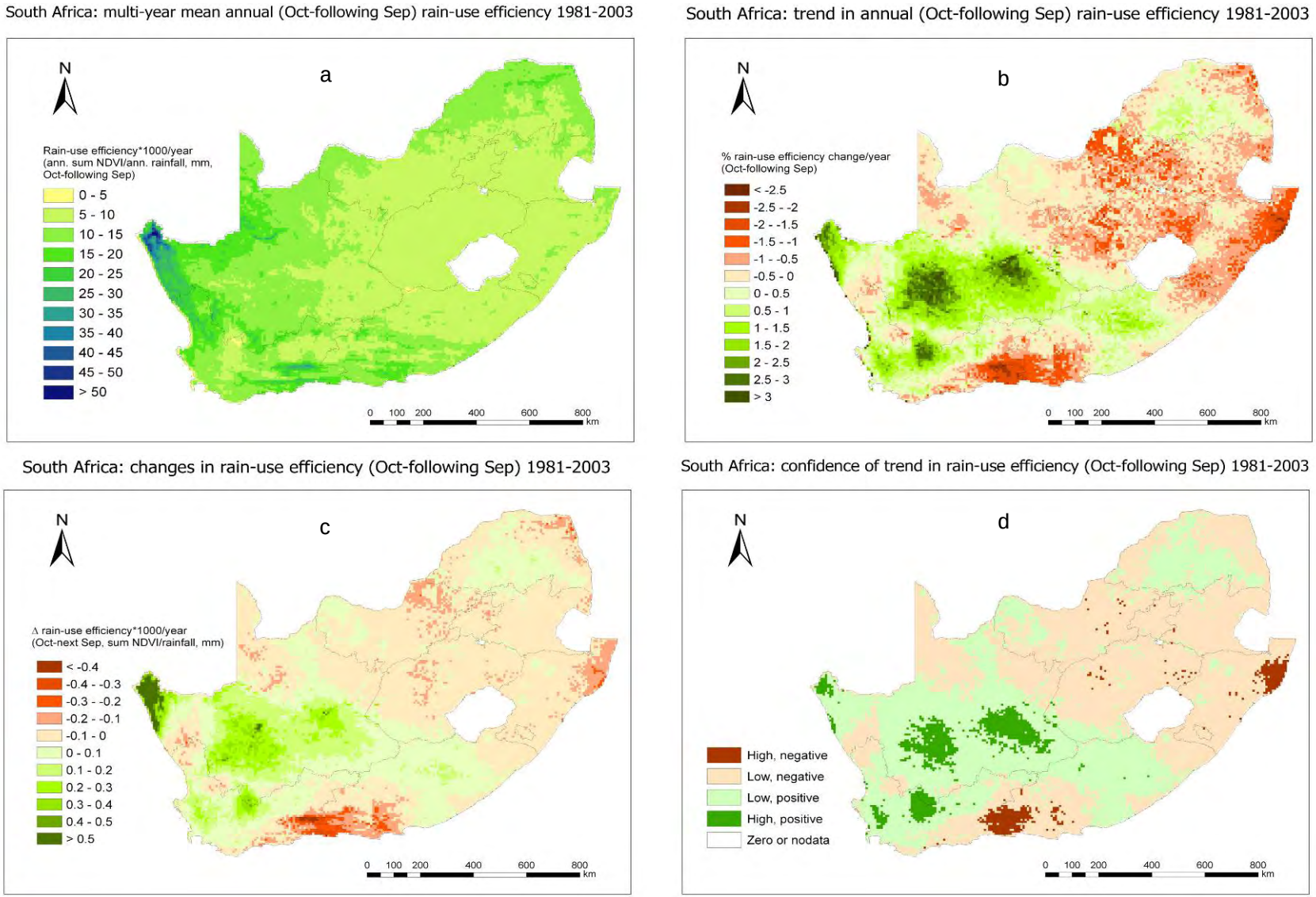


Figure 7. Rain-use efficiency 1981-2003: spatial pattern (a), temporal trend (b – percentage changes, c – absolute changes), confidence levels (d).

3.4 RESTREND

Countrywide, there is a significant negative correlation between RUE and rainfall ($r = -0.66$, $n = 21\,066$) and RUE fluctuates from year to year along with fluctuations of rainfall. This means that RUE, in isolation, says more about rainfall variability than about land degradation. To get around the correlations between RUE and rainfall, and distinguish land degradation from the effects of rainfall variability, Wessels and others (2007) suggest the alternative use of residual trends (RESTREND).

Following their general procedure, we have correlated for each pixel annual sum NDVI and annual rainfall (with the year running from October 1 through the following September to include the entire growing season). The resulting regression equation represents the statistical association between observed sum NDVI and rainfall (Figure 8a, b); the model predicts sum NDVI according to rainfall. Residuals of sum NDVI (i.e. differences between the observed and predicted sum NDVI) for each pixel were calculated, and the trend of these residuals was analysed by linear regression (Figure 8c). T-test confidence levels are shown in Figure 8d.

RESTREND points in the same direction as RUE: a negative RESTREND indicates land degradation, a positive RESTREND improvement. However, the spatial distribution is different from RUE; overall, RESTREND patterns are remarkably close to those of sum NDVI but of lesser amplitude (Figure 3c). See Section 3.9.

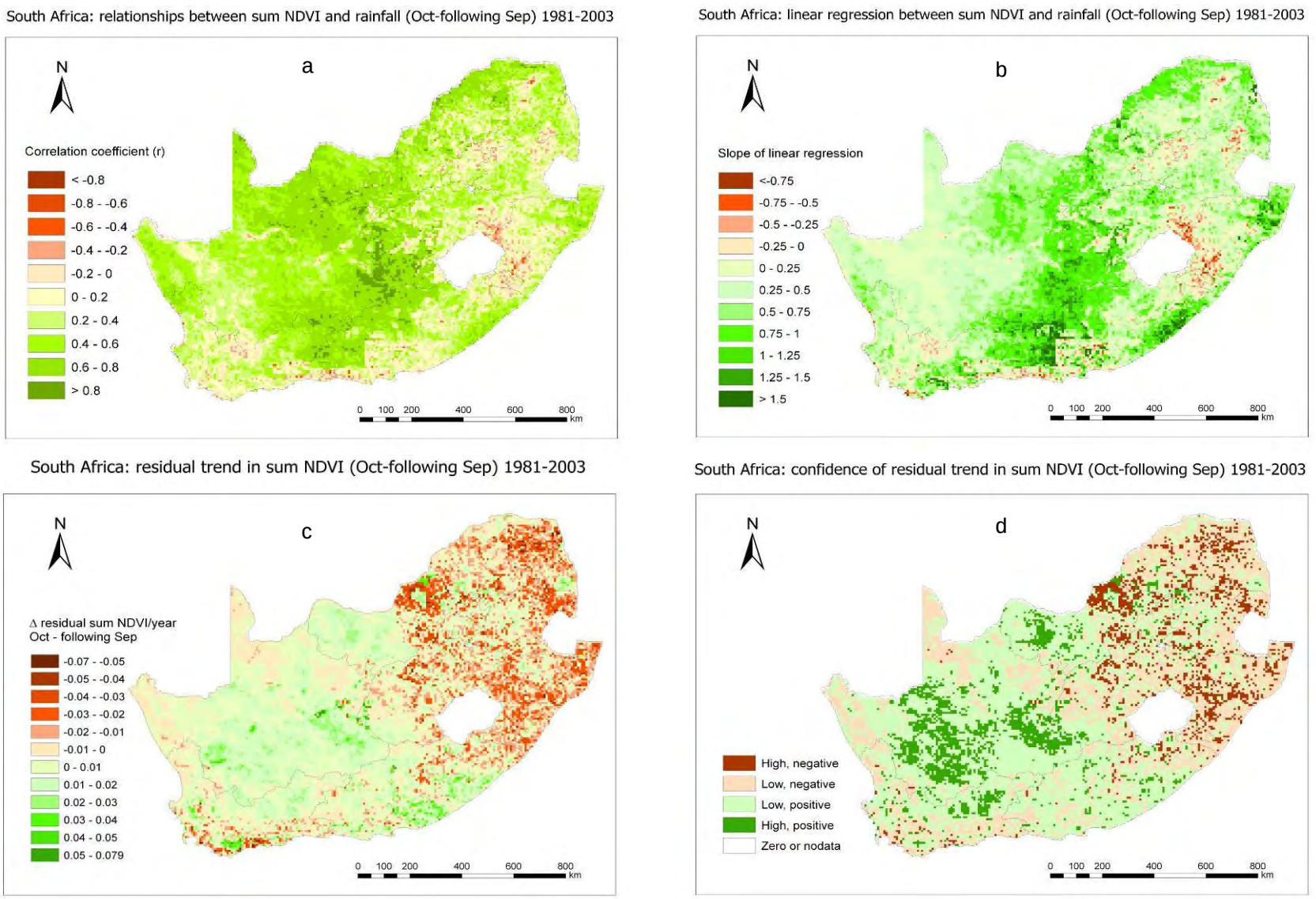


Figure 8. Residual trend of sum NDVI (RESTREND) 1981-2003 (a) Correlation coefficient between sum NDVI and annual rainfall; (b) Slope of linear regression between sum NDVI and rainfall; (c), RESTREND; (d) Confidence levels

3.5 Net primary productivity

It is hard to visualise the degree of land degradation and improvement from NDVI. For a quantitative estimation, NDVI may be translated to net primary productivity (NPP) - the rate at which vegetation fixes CO_2 from the atmosphere less losses through respiration; in other words, biomass productivity - which includes food, fibre and wood.

The most accessible global NPP data are from the MODIS model (at 1km resolution from the year 2000). Figure 9 shows four-year (2000-2003) mean annual MODIS NPP at 1-km resolution; the pattern is similar to GIMMS annual sum NDVI (Figure 3a) but at finer detail. We have translated the 1981-2003 GIMMS NDVI data to NPP by correlation with MODIS 8-day NPP values for the overlapping period.

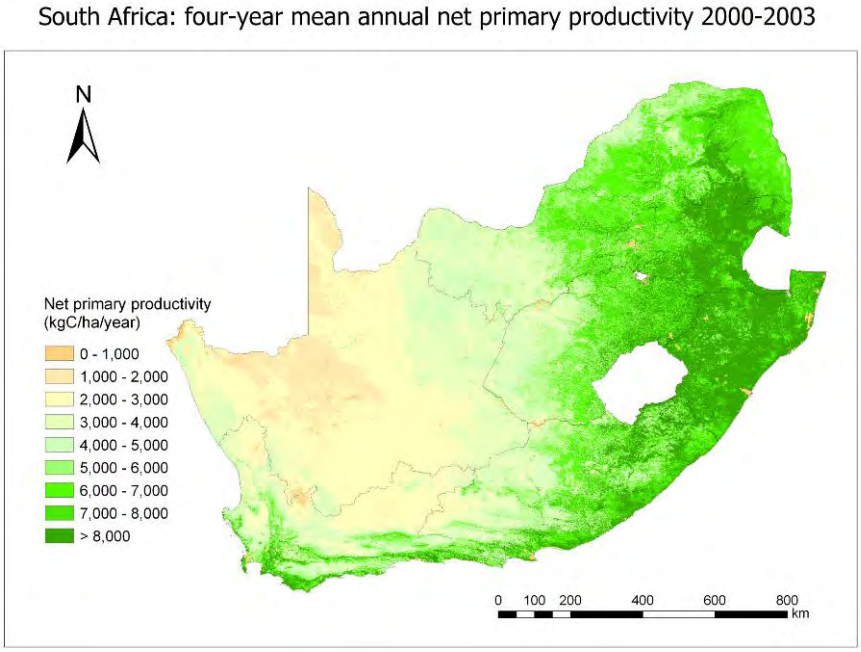


Figure 9. Mean annual NPP 2000-2003 derived from MOD17

MODIS four-year annual mean NPP was re-sampled to 8km resolution by nearest-neighbour assignment; the four-year mean annual sum NDVI over the same period (2000-2003) was then calculated:

$$NPP_{MOD17}\ [\text{tonneC ha}^{-1}\ \text{year}^{-1}] = 1.331 * NDVI_{sum} - 0.55 \quad [2]$$

($r^2 = 0.75$, n = 21 891, $P<0.001$)

Where NPP_{MOD17} is annual NPP derived from MOD17, $NDVI_{sum}$ is a four-year (2000-2003) mean annual sum NDVI derived from GIMMS.

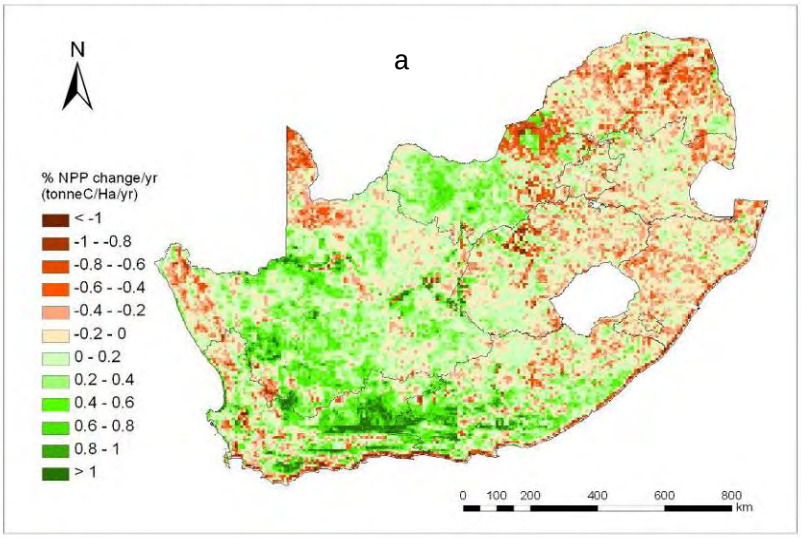
The statistical error in the regression model [2] is: slope (1.331) ± 0.025; intercept (-0.55) ± 0.108. The high coefficient of variation (r^2) indicates that MOD17A3 NPP can reasonably be used to convert the GIMMS NDVI values to NPP.

The percentage and absolute changes in NPP are depicted in Figure 10; the confidence level (Figure 10c) refers to the T-test (Appendix 1). Overall, NPP decreased during the period 1981-2003 (Table 1) because the areas suffering a decrease in NPP are, in general, in more productive areas.

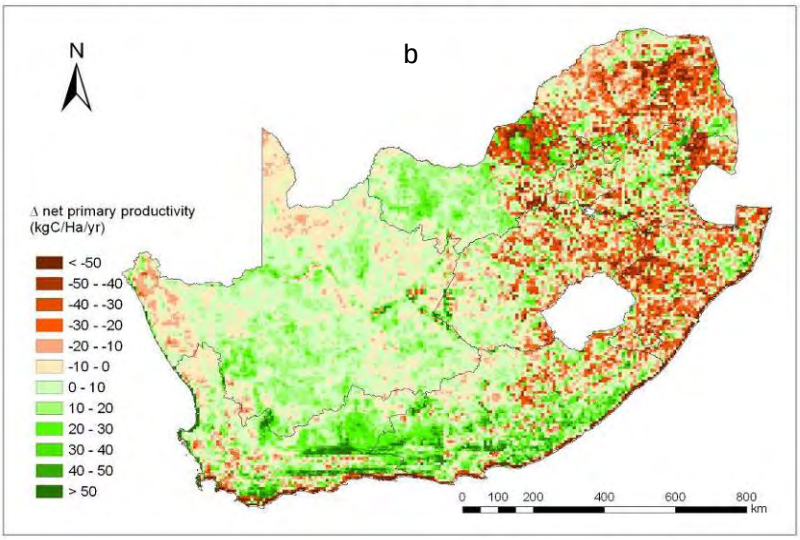
Table 1. Changes in net primary productivity 1981-2003

	Positive	*Negative*	*Average*
Land area (pixels, %)	54.7	45.3	
% NPP change/year (tonneC ha^{-1} $year^{-1}$)	0.28	0.22	0.06
Δ NPP (kgC ha^{-1} $year^{-1}$)	7.4	17.2	-8.6

South Africa: trend in annual (Oct-following Sep) net primary productivity 1981-2003



South Africa: change in annual (Oct-following Sep) net primary productivity 1981-2003



South Africa: confidence of trend in annual (Oct-Sep) sum NDVI 1981-2003

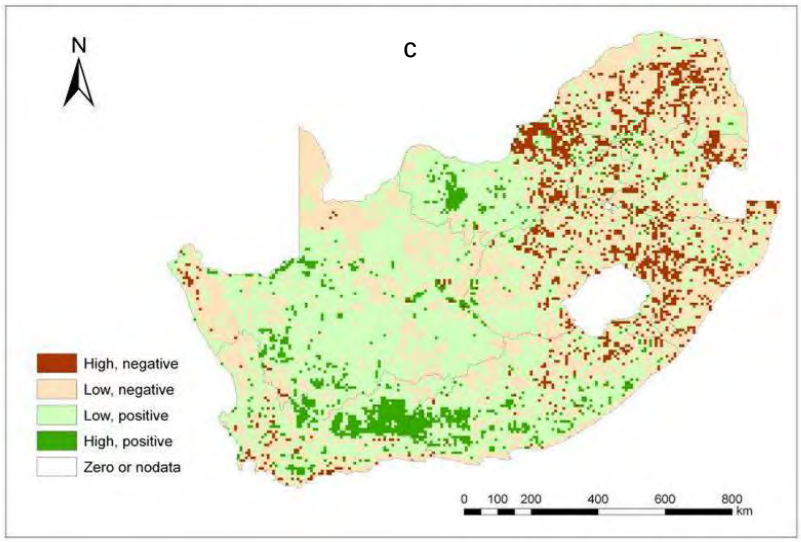


Figure 10. Changes in NPP 1981-2003
a – percentage change, b – absolute change, c – confidence level

3.6 Land degradation

Land degradation means a loss of NPP but a decrease in NPP is not necessarily land degradation. To distinguish between declining productivity caused by land degradation and decline due to other factors, it is necessary to eliminate false alarms arising from climatic variability and changes in land use and management.

Rainfall variability: has been taken into account by using both rain–use efficiency (RUE) and RESTREND. RUE is considered by, first, identifying pixels where there is a positive relationship between productivity and rainfall. For those areas where productivity depends on rainfall *and* where productivity declined but RUE increased, we attribute the decline of productivity to drought. Those areas are masked (urban areas are also masked). NDVI trends are presented for the remaining parts of the country as RUE-adjusted NDVI.

Twenty nine per cent of the country suffered declining RUE-adjusted NDVI, mostly in the north-east (Figure 11). Twenty per cent of the degrading area is in the communal lands, comprising 35 per cent of their total extent (Figure 12). These data confirm that land degradation is a serious issue in the communal lands but it is by no means confined to them; the proportion of degraded land in communal areas to the proportion in the country as a whole is 1.2:1.

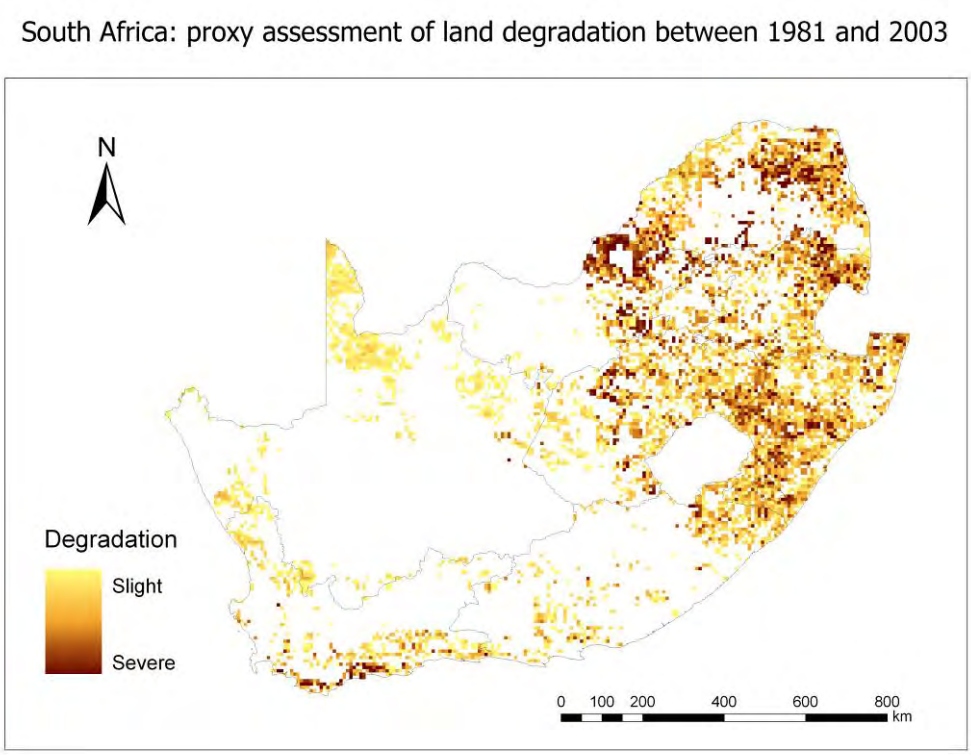


Figure 11. Negative trend in RUE-adjusted annual sum NDVI, 1981-2003

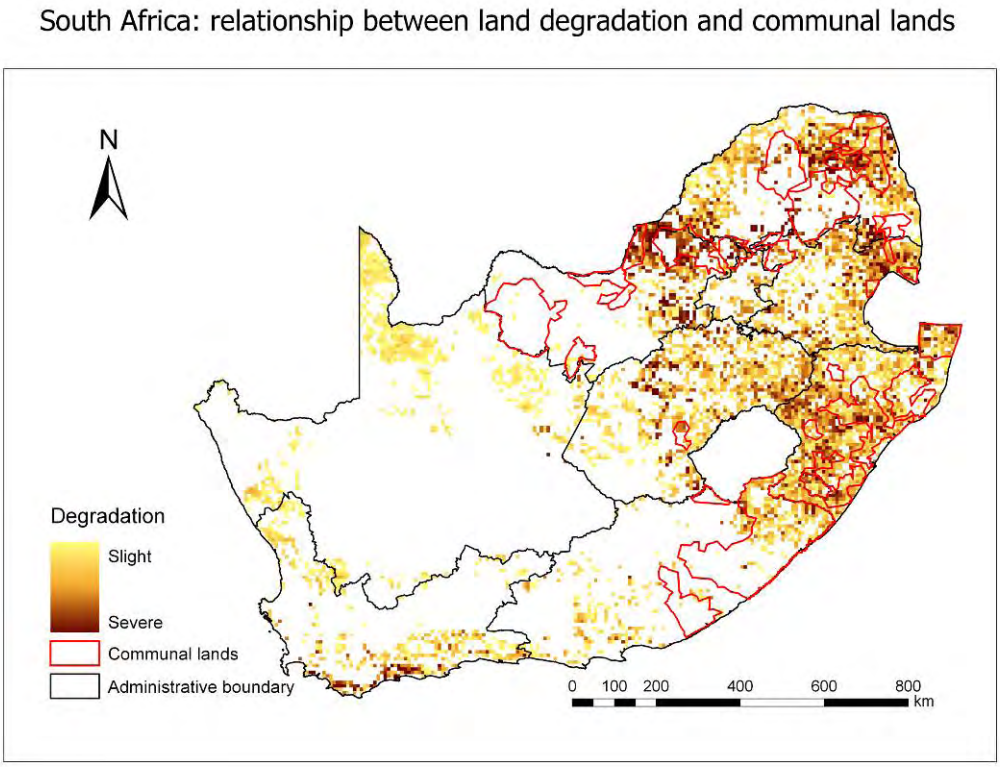


Figure 12. Communal lands boundaries overlaid on RUE-adjusted NDVI

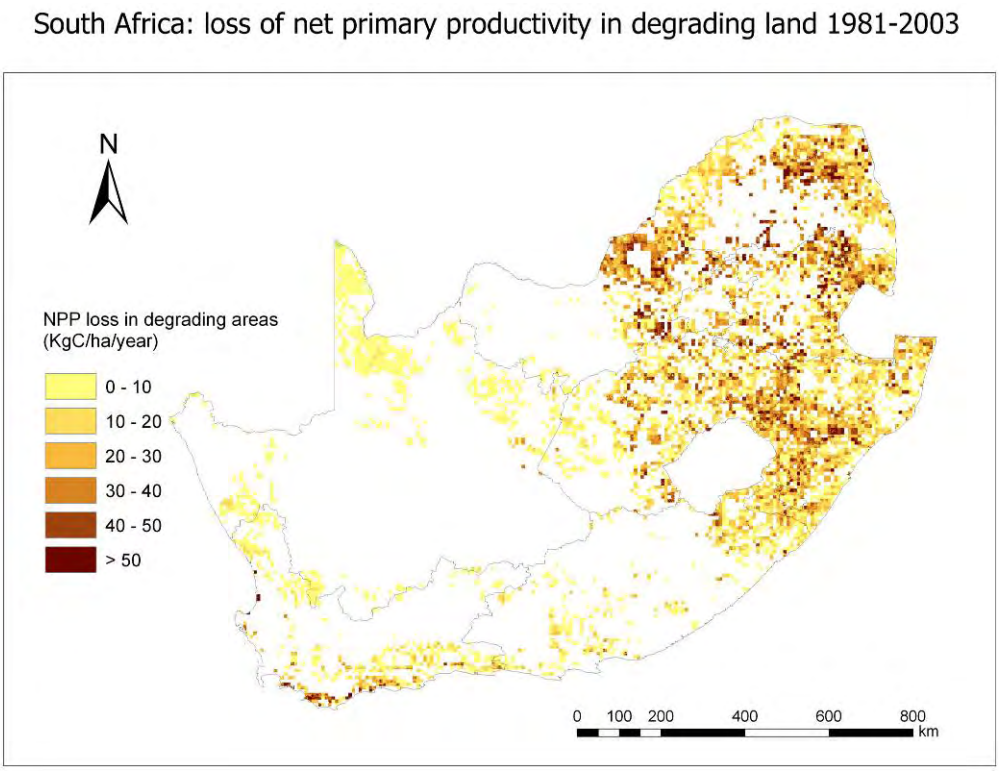


Figure 13. NPP loss in the degrading areas 1981-2003

Quantitative estimation: Figure 13 and Table 2 present a pixel-based estimate of the loss of NPP compared with the average over the period 1981-2003.

Table 2. South Africa and the World: NPP loss from degrading land

	Degrading land (km^2)	*% territory*	*% global degrading land*	*NPP loss (kg C/ha/yr*	*Total NPP loss (tonneC/23yr)*
South Africa	351 555	28.8	1.1	28.6	23 123 364
Globe	35 058 104	23.5	100	11.8	955 221 419

Land use change: As with rainfall variability, land use change may also generate false alarms about land degradation. Conversion of forest or grassland to cropland or pasture will usually result in an immediate reduction in NDVI (and NPP) but may well be profitable and sustainable, depending on management. Lack of consistent time series data for land use and management precludes a generalised analysis of land use change but this can be undertaken manually for the potential *hot spots* identified in this analysis.

3.7 Land improvement

Land improvement is identified by combination of: 1) a positive trend in sum NDVI for those areas where there is a no correlation between rainfall and NDVI; 2) for areas where NDVI is correlated with rainfall, a positive trend in rain-use efficiency; and 3) a positive trend in energy-use efficiency (Figure 14). Urban areas are masked. These areas account for about one third of the country. Figure 15 shows the gain in NPP in those areas.

3.8 Urban areas

Whether urbanisation is degradation is arguable. It brings a huge increase in the financial value of the land but, if it involves surface sealing, it is degradation according to our criterion of partial loss of ecosystem function. The CIESIN Global Rural Urban Mapping Project shows 3.6 per cent of South Africa as urban area and this area is masked in the maps. Masking the urban area makes only a small difference to the results: a reduction of 2 per cent for the identified degrading land, and a reduction of 0.3 per cent for the improving land.

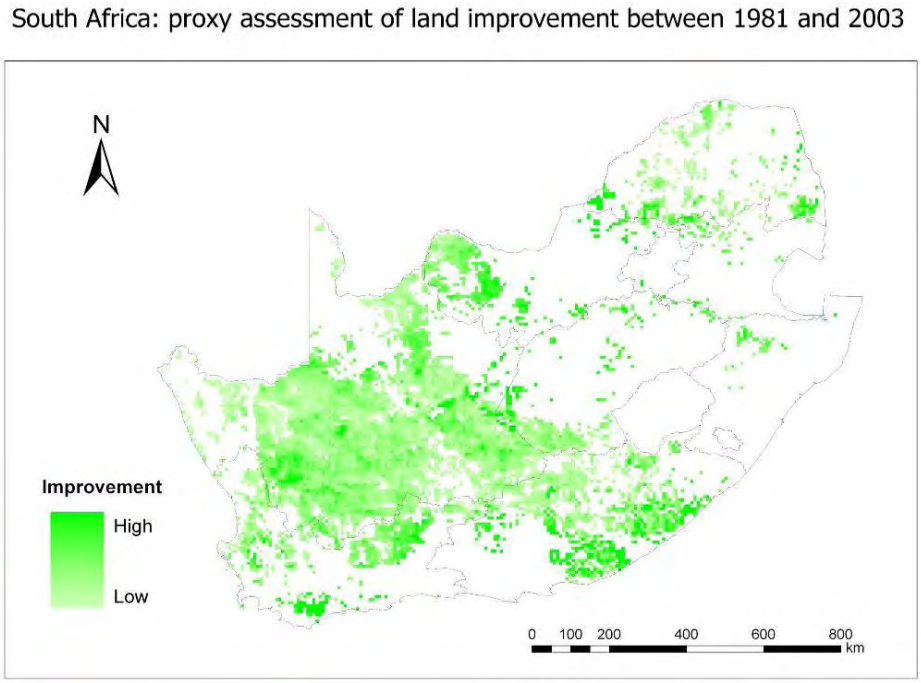


Figure 14. Areas of increasing NPP, RUE and EUE, 1981-2003

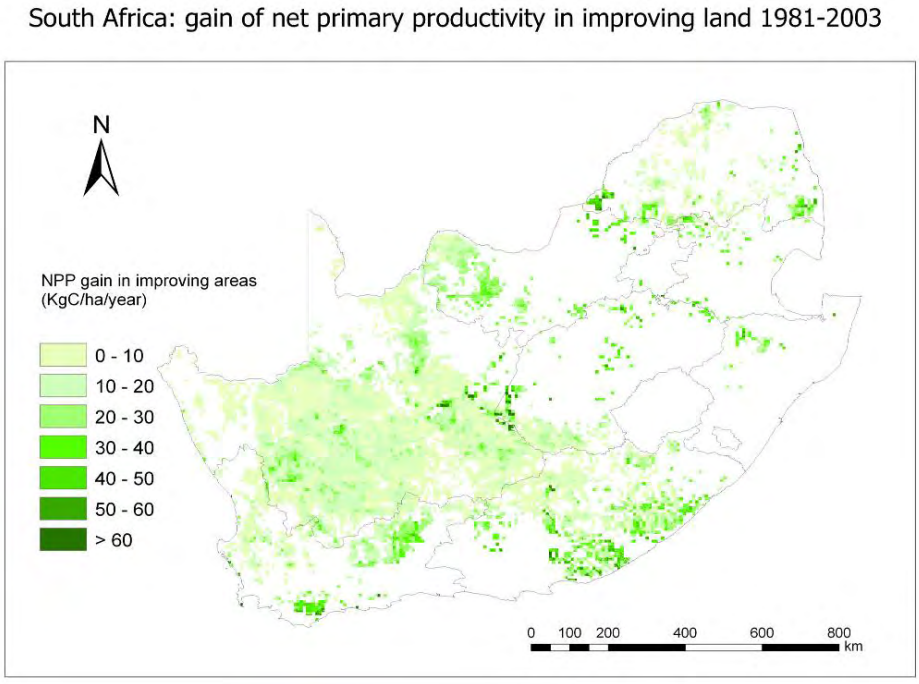


Figure 15. NPP gain in the improving areas 1981-2003

3.9 Comparison of indicators

Annual sum NDVI is our standard indicator of productivity. Rain-use efficiency, RESTREND and RUE-adjusted NDVI and are different ways of eliminating false alarms about land degradation caused by the variability of rainfall; each of these measures is useful in its own right. An advantage of RUE-adjusted NDVI is that, for areas considered as degrading or improving, the original NDVI values are retained and can be converted to NPP - which is open to economic analysis. Negative RUE-adjusted NDVI and negative RESTREND show similar patterns (cf Figures 11 and 8c) but negative RESTREND encompasses a somewhat larger area.

Table 3 presents a comparison of indicators. If we take a negative RUE-adjusted NDVI as the primary definition of degrading areas, then 89 per cent of the degrading land shows negative trends in both sum NDVI and RESTREND. Taking a positive trend of RUE-adjusted NDVI as the primary definition of improving land, 88 per cent also shows positive trend in both sum NDVI and RESTREND.

Comparing RUE with RESTREND, almost all of the areas defined as improving according to RUE-adjusted NDVI also show a positive trend in RESTREND and 95 per cent of the areas defined as degrading according to RUE-adjusted NDVI also shows negative trend in RESTREND.

Table 3. Comparison of trends in various indicators

Indicators	*Total pixel*	*Negative trend*	*Positive trend*	*No change*	*Mixed*
	(%)	(%)	(%)	(%)	(%)
Annual sum NDVI	100	45.3	54.7	0.05	0.0
RESTREND[1]	100	40.9	57.6	1.5	0.0
Sum NDVI ∩ RESTREND	100	35.1	48.1	1.5	15.3
Sum NDVI ∩ RESTREND within LI[2]			**88.3**		
Sum NDVI ∩ RESTREND within LD[3]		**88.7**			
RUE	100	53.8	44.7	1.5	
RUE ∩ RESTREND	100	33.6	37.4	1.5	27.5
RUE ∩ RESTREND within LI			**99.9**		
RUE ∩ RESTREND within LD		**95.3**			

[1] Residual trend of sum NDVI; [2] LI - identified improving land; [3] LD - identified degrading land.

3.10 Analysis of degrading and improving areas

3.10.1 Association with land cover and land use

Comparing degrading and improving areas, defined by the 1981-2003 trends of climate-adjusted NDVI, with land cover in the year 2000 (Figure 1 and Table 4): 29 per cent of the degrading area is cropland (41 per cent of all cropland); 33 per cent is forest (55 per cent of forest) and 37 per cent is rangeland (shrub and herbaceous cover in Table 4). Only 9 per cent of the improving area is cropland; 7 per cent is forest, and 84 per cent is rangeland.

Table 4. Degrading and improving land by land cover

Code	*Land cover*	*Total pixels (TP)*[1]	*Degrading pixels (DP)*[2]	*DP/TP*	*DP/TDP*[3]	*Improving pixels (IP)*	*IP/TP*	*IP/TIP*[4]
				(%)	*(%)*		*(%)*	*(%)*
1	Tree cover, broadleaved evergreen	10 040	5032	50.1	1.2	423	4.2	0.1
2	Tree cover, broadleaved deciduous, closed	60 650	35860	59.1	8.9	5 129	8.5	1.1
3	Tree cover, broadleaved deciduous, open	170 254	91391	53.7	22.7	26 787	15.7	5.9
9	Mosaic: tree cover/ other natural vegetation	3 525	1644	46.6	0.4	514	14.6	0.1
12	Shrub cover, closed-open, deciduous	412 461	92418	22.4	22.9	138 387	33.6	30.5
13	Herbaceous cover, closed-open	243 693	39991	16.4	9.9	106 312	43.6	23.5
14	Sparse herbaceous or shrub cover	209 602	17179	8.2	4.3	136 200	65.0	30.0
15	Regularly flooded shrub and/or herbaceous	343	166	48.4	0.0	0	0.0	0.0
16	Cultivated and managed	285 554	116628	40.8	28.9	39 485	13.8	8.7
17	Mosaic: cropland/tree cover/other natural vegetation	1 942	1352	69.6	0.3	0	0.0	0.0
19	Bare	4 350	0	0.0	0.0	0	0.0	0.0
20	Water bodies	7333	0	0	0	0	0	0
22	Artificial surfaces	8 394	1375	16.4	0.3	115	1.4	0.0
	Total	1418141	403036		100	453 352		100.0

[1] Pixel size: 1 x 1 km, [2] urban areas are excluded, [3] TDP - Total degrading pixels, [4] TIP - Total improving pixels

Comparing degrading areas with land use (Tables 5 and 6), 30 per cent of degrading land is under various categories of forestry, 36 per cent is grassland (herbaceous in the FAO key), 29 per cent is agricultural land, and less than 4 per cent is made up of wetland, bare and urban areas. In contrast, 83 per cent of improving land is grassland, 9 per cent is agricultural land, and 7 per cent is forest.

Table 5. Degrading and improving areas by land use systems (FAO 2008)

Code	*Land use system*	*Total pixels (TP)*	*Degrading pixels (DP)*	*DP/TP %*	*DP/TDP[1] %*	*Improving pixels (IP)*	*IP/TP %*	*IP/TIP[2] %*
0	Undefined	0	0	0.0	0.00	0	0.0	0.00
1	Forestry - no use / not managed (Natural)	252	144	57.1	3.13	29	11.5	0.55
2	Forestry - Protected areas	324	177	54.6	3.85	31	9.6	0.59
4	Forestry - Pastoralism moderate or higher	1222	645	52.8	14.03	201	16.4	3.81
5	Forestry - Pastoralism moderate or higher with scattered plantations	665	394	59.2	8.57	98	14.7	1.86
6	Forestry - Scattered plantations	68	37	54.4	0.81	4	5.9	0.08
7	Herbaceous - no use / not managed (Natural)	121	35	28.9	0.76	32	26.4	0.61
8	Herbaceous - Protected areas	408	184	45.1	4.00	78	19.1	1.48
9	Herbaceous - Extensive pastoralism	4653	554	11.9	12.05	2458	52.8	46.62
10	Herbaceous - Mod. Intensive pastoralism	3715	621	16.7	13.51	1520	40.9	28.83
11	Herbaceous - Intensive pastoralism	930	274	29.5	5.96	282	30.3	5.35
13	Rain fed Agriculture (Subsistence / commercial)	421	131	31.1	2.85	96	22.8	1.82
14	Agro-pastoralism Mod. Intensive	1938	796	41.1	17.32	244	12.6	4.63
15	Agro-pastoralism Intensive	636	289	45.4	6.29	87	13.7	1.65
16	Agro-pastoralism mod. intensive or higher with Large scale irrigation	110	41	37.3	0.89	27	24.5	0.51
17	Agriculture - Large scale irrigation (> 25% pixel size)	44	15	34.1	0.33	7	15.9	0.13
18	Agriculture - Protected areas	88	55	62.5	1.20	10	11.4	0.19
19	Urban areas	564	180	31.9	3.92	43	7.6	0.82
20	Wetlands - no use / not managed (Natural)	4	2	50.0	0.04	0	0.0	0.00
21	Wetlands - Protected areas	0	0	0.0	0.00	0	0.0	0.00
22	Wetlands - Mangroves	0	0	0.0	0.00	0	0.0	0.00
23	Wetlands - Agro-pastoralism	0	0	0.0	0.00	0	0.0	0.00
24	Bare areas - no use / not managed (Natural)	5	2	40.0	0.04	2	40.0	0.04
25	Bare areas - Protected areas	1	0	0.0	0.00	0	0.0	0.00
26	Bare areas - Extensive pastoralism	34	2	5.9	0.04	10	29.4	0.19
27	Bare areas - Mod. Intensive pastoralism or higher	3	2	66.7	0.04	1	33.3	0.02
28	Water - Coastal or no use / not managed (Natural)	11	2	18.2	0.04	1	9.1	0.02
29	Water - Protected areas	22	9	40.9	0.20	2	9.1	0.04
30	Water - Inland Fisheries	22	5	22.7	0.11	9	40.9	0.17
100	Undefined	0	0		0.00	0	0.0	0.00
	Total	16261	4596		100.00	5272		100.00

[1]TDP - total degrading pixels; [2]TIP - total improving pixels

Table 6. Degrading / improving lands in the aggregated land use systems

Land use system	*Codes*	*Total pixels (TP)*	*Degrading pixels (DP)*	*DP/TP*	*DP/TDP*[1]	*Improving pixels (IP)*	*IP/TP*	*IP/TIP*[2]
(LUS)		(5'x5')	(5'x 5')	(%)	(%)	(5'x 5')	(%)	(%)
Forestry	1-6	2531	1397	55.2	30.4	363	14.3	6.9
Grassland	7-11	9827	1668	17.0	36.3	4370	44.5	82.9
Agricultural land	13-18	3237	1327	41.0	28.9	471	14.6	8.9
Urban	19	564	180	31.9	3.9	43	7.6	0.8
Wetlands	20-23	4	2	50.0	0.04	0	0.0	0.0
Bare areas	24-27	43	6	14.0	0.1	13	30.2	0.2
Water	28-30	55	16	29.1	0.3	12	21.8	0.2
Undefined	0,100	0	0	0.0	0.0	0	0.0	0
Total		16261	4596		100.0	5272		100

[1]TDP - total degrading pixels, [2]TIP - total improving pixels

3.10.2 Association with population density

38 per cent of the South African population (17 million out of 44.7 million in 2005) lives in the areas afflicted by land degradation (Figure 16) the communal areas of Kwazulu Natal, Transkei and Gazankulu are severely affected. The correlation between land degradation and $\log_e$ population density is weakly positive (r^2=0.1) - the higher the population density, the more land degradation (Figure 17).

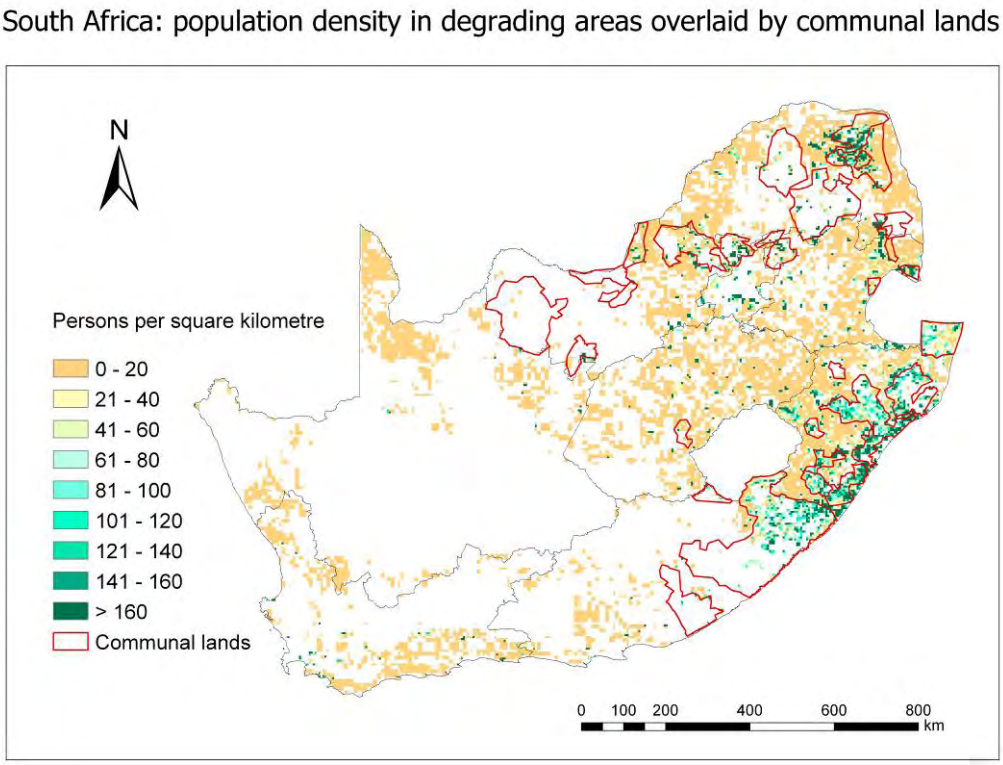


Figure 16. Population counts affected by the land degradation

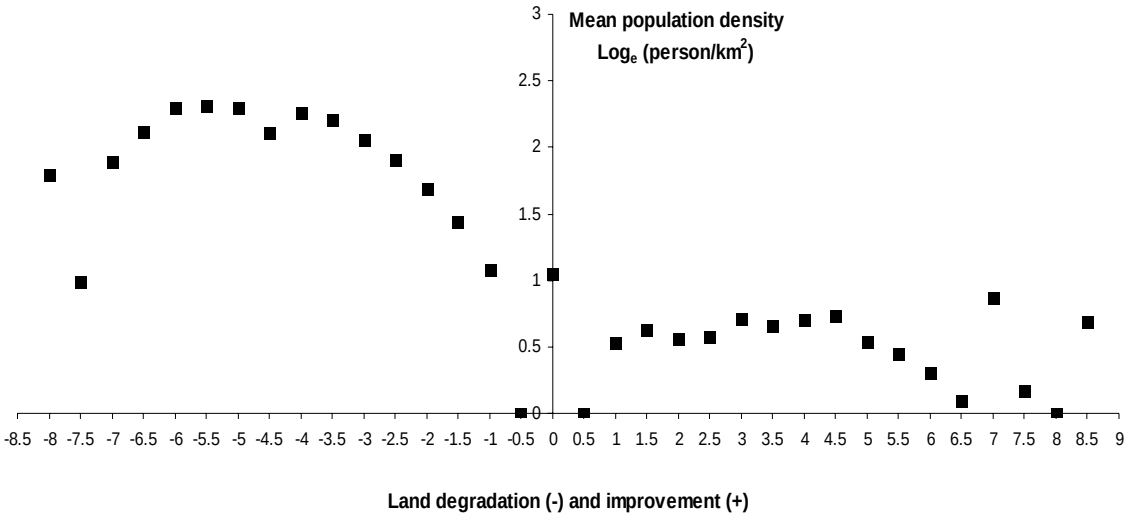


Figure 17. Relationship between population density and land degradation and improvement

3.10.3 Relationship with soils and terrain

Figure 18 depicts several individual soil-and-terrain attributes for South Africa. There is no obvious relationship between land degradation and any individual attribute:

- For soil organic carbon, classes defined by 0-5, 5-10, 10-30 and >30 g/kilogram, occupy 34, 45, 20 and 1 per cent of the degrading area, respectively (Figure 19), which is similar to the national extent of each class (Table 7);

- With respect to terrain, more than 63 per cent of the degrading land is flat and some 28 per cent is medium-gradient, rather than steeply sloping (Table 8).

It appears that land degradation at the 100 km^2 scale depends upon management rather than upon soils and terrain *per se*.

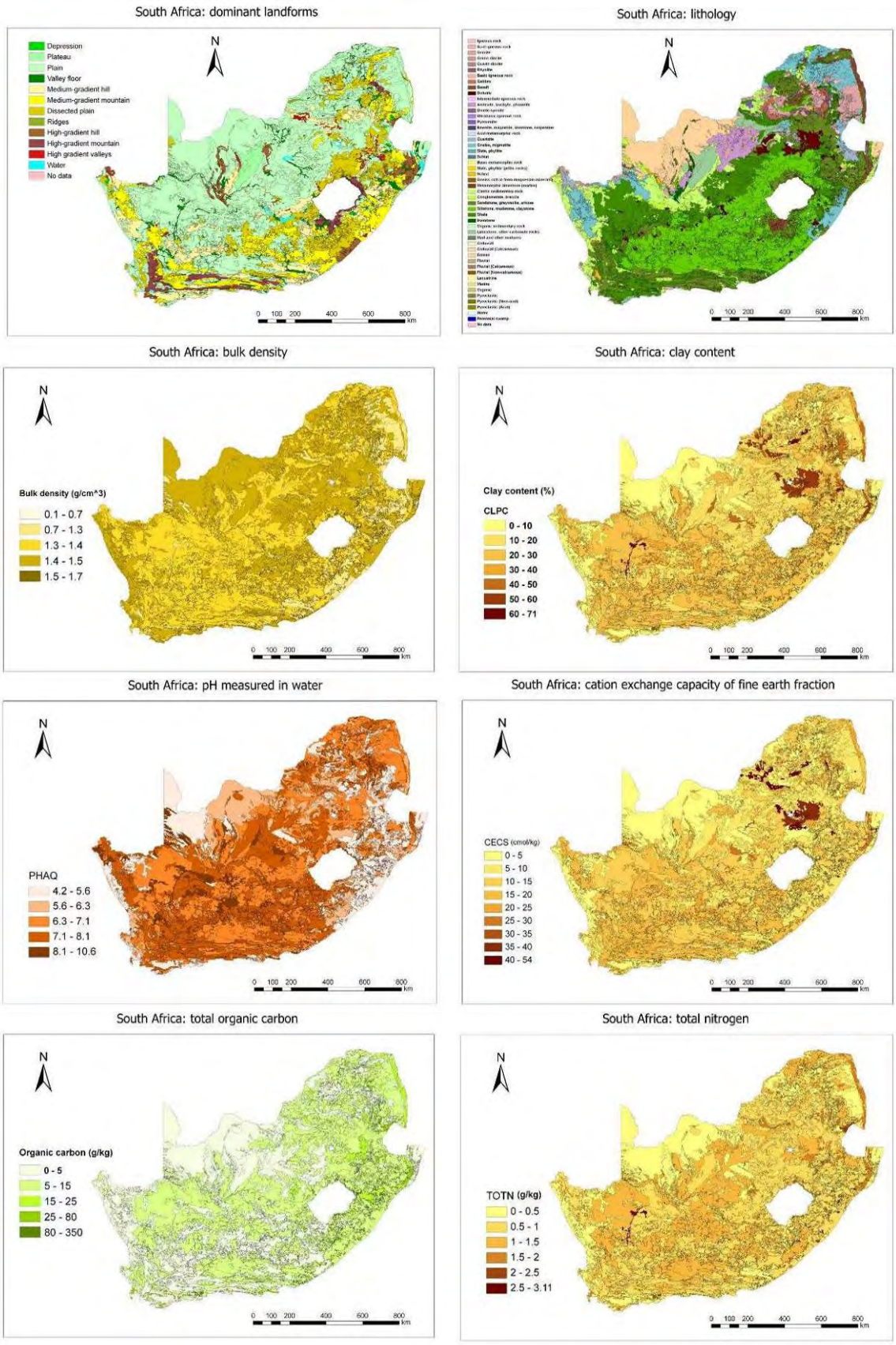


Figure 18. Soil and terrain attributes for dominant soil types

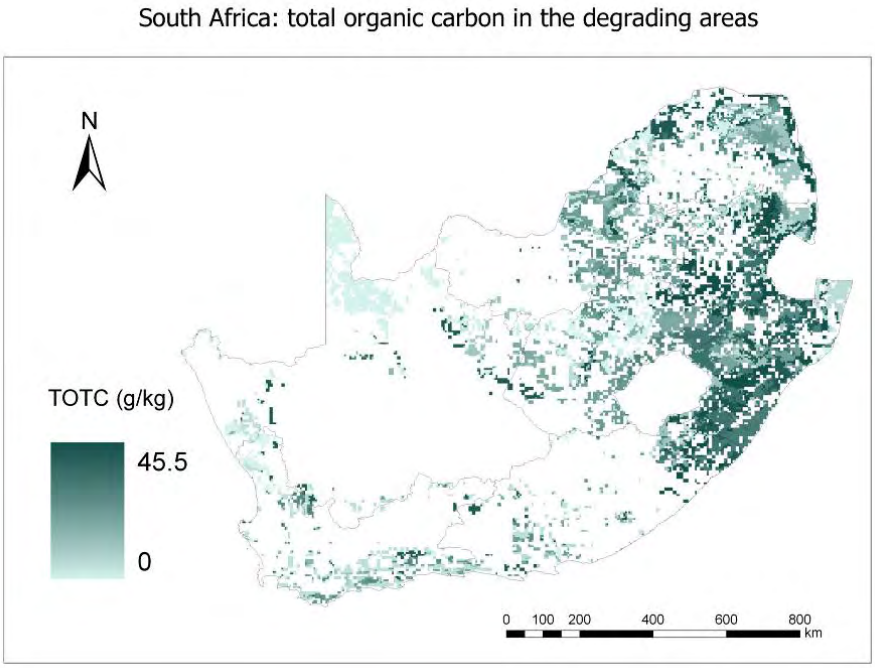


Figure 19. Total soil organic carbon in degrading areas

Table 7. Total soil organic carbon in degrading areas

TOTC (g/kg)	*Pixels in class*	*%*	*Pixels in degrading land*	*%*
0 - 5	28 511	43.8	6273	33.7
5 - 10	23 605	36.2	8499	45.7
10 - 30	12 816	19.7	3782	20.3
> 30	192	0.3	54	0.3
Total	65 124	100	18608	100

Table 8. Land degradation in different landforms

SOTER label	*Landforms*	*Pixels in class*	*% of total pixel*	*Degrading pixels*	*% of degrading pixel*
LD	Depression	30	0.1	16	0.3
LL	Plateau	350	1.6	107	1.7
LP	Plain	11 655	54.8	2 855	46.4
LV	Valley floor	606	2.8	193	3.1
SH	Medium-gradient hill	2 370	11.1	825	13.4
SM	Medium-gradient mountain	2 679	12.6	916	14.9
SP	Dissected plain	2 216	10.4	796	12.9
SR	Ridges	11	0.1	9	0.1
TH	High-gradient hill	522	2.5	137	2.2
TM	High-gradient mountain	670	3.1	228	3.7
TV	High gradient valleys	154	0.7	70	1.1
Wat	Water	23	0.1	0	0.0
Total		21286	100.0	6152	100.0

3.10.4 Relationship with aridity

There is no obvious relationship between land degradation and Turc's aridity index (r^2=0.01); 37 per cent of degrading areas are in humid regions, 20 per cent in dry sub-humid, 31 per cent in semi-arid, and 12 per cent in arid and hyper-arid regions.

3.10.5 Relationship with poverty

Taking infant mortality rate and the percentage of children younger than five years who are underweight as proxies for poverty, there is a weakly negative relationship between land degradation and percentage of children underweight (r^2=0.05); there is almost no correlation between land degradation and infant mortality. A more rigorous analysis is needed to tease out the underlying biophysical and social and economic variables.

4 What GLADA can and cannot do

- We have defined land degradation as a long-term loss of ecosystem function and we use net primary productivity (NPP) as an indicator. GLADA is an interpretation of GIMMS time series NDVI data, i.e. greenness, which is taken as a proxy for NPP. Translation of NDVI to NPP is robust but approximate.

- The proxy is several steps removed from the recognisable symptoms of land degradation as it is commonly understood – such as soil erosion, salinity or nutrient depletion; the same goes for land improvement.

- Greenness is determined by several factors. To interpret it in terms of land degradation and improvement, these other factors must be accounted for – in particular, variability of rainfall and changes in land use and management. Rain-use efficiency (RUE, NPP per unit of rainfall) accounts for rainfall variability and, to some extent, local soil and land characteristics. We assume that, where NPP is limited by rainfall, a declining trend in RUE indicates land degradation. Where rainfall is not limiting, NPP is the best indicator available. Taken together, the two indicators may provide a more robust assessment than either used alone. Alternatively, RESTREND points in the same direction; it shows much the same pattern as the sum NDVI though with lesser amplitude. Land use change is not accounted for in this study for lack of consistent time series data.

- Declining NPP, even allowing for climatic variability, may not even be reckoned as land degradation; urban development is generally considered to be *development* – although it generally means a long-term loss of ecosystem function; land use change from forest or grassland to cropland or rangeland may or may not be accompanied by soil erosion, compaction and nutrient depletion, and it may well be profitable and sustainable, depending on management. Similarly, an increasing trend of NPP means greater biological production but may reflect, for instance encroachment of bush or invasive species – which is not land improvement as it is commonly understood.

- The 8km resolution of the GIMMS data is a limitation: an 8km pixel integrates the signal from a wider surrounding area. Many symptoms of even very severe degradation, such as gullies, rarely extend over such a large area; degradation must be severe to be seen against the signal of surrounding unaffected areas. In South Africa, a more detailed analysis is possible using its long time series of 1km-resolution NDVI data (Wessels and others 2004).

- As a quantitative measure of land degradation, loss of NPP relative to the average trend has been calculated for those areas where *both* NPP and RUE are declining. This is likely to be a conservative estimate: where NPP is increasing but RUE is declining, some process of land degradation may have begun that is reducing NPP but is not yet reflected in declining NPP.

- By the same reasoning, RUE should be used alone for *early warning* of land degradation, or a herald of improvement. Where NPP is rising but RUE declining, some process of land degradation might be under way that is not yet reflected in declining NPP; it will remain undetected if we consider only those areas where both indices are declining. The reverse also holds true: we might forgo promising interventions that increase RUE but have not yet brought about increasing NPP.

- GLADA presents a different picture from previous assessments of land degradation which compounded historical land degradation with what is happening now. The data from a defined, recent period indicate current trends but tell us nothing about the historical legacy; many degraded areas have become stable landscapes with a stubbornly low level of productivity. For many purposes, it is more important to address present-day land degradation; much historical land degradation may be irreversible.

- Remote sensing provides only indicators of trends of biomass productivity. The various kinds of land degradation and improvement are not distinguished; the patterns derived from remote sensing should be followed up by fieldwork to establish the actual conditions on the ground. Results remain provisional until validated in the field but an 8km pixel, or even a 1km pixel, cannot be checked by a windscreen survey; and a 23-year trend cannot realistically be checked by a snapshot. A rigorous procedure must be followed, as defined in the forthcoming *LADA Field Handbook*. Apart from systematically and consistently characterising the situation on the ground across a range of scales, the field teams may validate the GLADA interpretation by addressing the following questions:

    1. Is the biomass trend indicated by GLADA real?
    2. If so, does it correspond with physical manifestations of land degradation or improvement that are measurable on the ground?
    3. In the case of a negative answer to either of the preceding questions, what has caused the observed biomass trend?
    4. Is the mismatch a question of timing of observations – where the situation on the ground has subsequently recovered, or fallen back?

5 Conclusions

5.1 Land degradation is defined as a long-term decline in ecosystem function and measured in terms of net primary productivity; the remotely-sensed normalised difference vegetation index (NDVI) is used as a proxy. Rainfall variability is taken account of by rain-use efficiency-adjusted NDVI and residual trends of the rainfall-NDVI relationship (RESTREND), temperature by using energy-use efficiency. Spatial patterns and trends of NDVI combined with climatic indices are analysed for the period 1981-2003 at 8km resolution. NDVI is translated to NPP; land degradation is indicated by a declining trend of climate-adjusted NPP and land improvement by an increasing trend.

5.2 In South Africa, net primary productivity decreased over the period 1981-2003. Areas of decreasing climate-adjusted NPP occupy some thirty per cent of the country, mostly in the north-east. Twenty-nine per cent of the degrading area, so defined, is cropland – 41 per cent of all cultivated areas; 33 per cent is forest (55 per cent of the forest area); and 37 per cent rangeland. Overall, these areas suffered an average loss of NPP of 29 kg C/ha/year. This loss of biological productivity means an economic loss in terms of crop yields and the production of rangeland and forest; it also has biological meaning *of itself* – decline of biomass production is an aggregation of declining ecosystem functions like carbon sequestration and carbon stocks, and in many cases will be related to a loss of biodiversity.

5.3 This significant loss of biological productivity has occurred at the same time as South Africa's population increased by 50 per cent (from 30 to 45 millions). About 17 million people (38 per cent of the population) live in the degrading areas.

5.4 There is a weak correlation between degrading land and rural population density; degradation is somewhat over-represented in the communal lands but by no means confined to them. There is no obvious relationship between degrading land and soil or terrain, and only a weak correlation with aridity: 37 per cent of degrading areas are in humid regions, 20 per cent in dry sub-humid, 31 per cent in semi-arid, and 12 per cent in arid and hyper-arid regions. Land degradation appears to be driven by management.

5.5 One third of the country shows an increase in climate-adjusted net primary productivity. Most of these areas are in the west of the country; 84 per cent is rangeland, 9 per cent cropland and 7 per cent forest.

5.6 GLADA presents a different picture from previous assessments of land degradation which compounded historical land degradation with what is happening now. The data from a defined, recent period indicate current trends and, for many purposes, it is more important to address what is happening now: much of the historical legacy may be irreversible.

5.7 GLADA provides a globally consistent yardstick but only a proxy assessment of land degradation and improvement. The various kinds of degradation and improvement are not distinguished and analysis is constrained by the 8km resolution of the GIMMS data. Results are provisional until validated in the field but checks must take account of their coarse resolution and the fact that they integrate change over most of the last 25 years; they cannot be checked by windscreen survey and snapshots.

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Appendix 1: Analytical methods

Derivation of NDVI indicators

ArcGIS Spatial Analyst, ERDAS IMAGINE and ENVI-IDL were used to calculate NDVI minimum, maximum, maximum-minimum, mean, sum, standard deviation (STD) and coefficient of variation (CoV), as well as climate variables. The fortnightly NDVI data were geo-referenced and averaged to monthly; annual NDVI indicators from 1 October to following 30 September were derived for each pixel; their temporal trends were determined by linear regression at an annual interval and mapped to depict spatial changes (Appendix 2).

A negative slope of linear regression indicates a decline of green biomass and a positive slope, an increase – except for STD and CoV which indicate trends in variability. The absolute change (Δ in map legends, titled "changes in …..") is the slope of the regression; the relative change (% in map legends, titled "trend in ….") is 100(slope of the regression/multi-year mean).

Monthly grids of rainfall for the period 1981-2002 were geo-referenced and re-sampled to the same spatial resolution as the NDVI (8km) using neighbourhood statistics. Spatial pattern and temporal trend of rainfall and rain-use efficiency (RUE, the ratio of annual NDVI and annual rainfall) for each pixel were determined by regression.

Land degradation was identified by negative trends of both biomass and rain-use efficiency. To distinguish between declining productivity caused by land degradation, and declining productivity due to other factors, rainfall variability has been accounted for by, first, identifying pixels where there is a positive relationship between productivity and rainfall; secondly, for those areas where productivity depends on rainfall, rain-use efficiency has been considered: where productivity declined but RUE increased, we attribute the decline of productivity to declining rainfall and those areas are masked. Land improvement was identified by positive changes in sum NDVI where show positive rain-use efficiency which has a positive correlation between sum NDVI and rainfall and energy-use efficiency. Both were masked by the mapped urban extents.

Statistical tests

The trend analysis assumes that the data are spatially and temporally independent. This was tested by examining autocorrelation coefficients following Livezy and Chen (1983). When the absolute values of the autocorrelation coefficients of lag-1 to lag-3 calculated for a time series consisting of *n* observations are not larger than the typical critical value corresponding to 5 per cent significance level, i.e., $1.96/\sqrt{n}$, the observations in this time series can be accepted as being independent from each other.

The T-test was used to arrange the slope values in classes showing strong or weak positive or negative trends:

$$T = b / se(b)$$

Where *b* is the calculated slope of the regression line between the observation values and time and *se(b)* represents the standard error of *b.*

The class boundaries were defined for 95 per cent confidence level; trends were labelled *high* if the *T*-values of the slope exceeded the 0.025 *p*-value of either tail of the distribution; lesser *T*- values were labelled *low*.

In addition, SPSS and MS Excel were employed to analyze trends, correlations and significances of the non-gridded variables.

Associations between land degradation/improvement and other variables

Maps of the degrading areas or improving areas were overlaid on the other maps. Corresponding comparative values were calculated, pixel-by-pixel and a univariate correlation calculated.

Appendix 2: NDVI indicators of the land degradation / improvement

Minimum NDVI: The lowest value that occurs in any one year (annual) - which is usually at the end of the dry season. Variation in minimum NDVI may serve as a baseline for other parameters.

Maximum or peak NDVI: Represents the maximum green biomass. The large spatial variations reflect the diverse landscapes and climate.

Maximum-minimum NDVI: The difference between annual maximum and minimum NDVI reflects annual biomass productivity for areas with one, well-defined growing season but may not be meaningful for areas with bimodal rainfall.

Sum NDVI: The sum of fortnightly NDVI values for the year most nearly aggregates annual biomass productivity.

Standard deviation (STD): NDVI standard deviation is the root mean square deviation of the NDVI time series values (annual) from their arithmetic mean. It is a measure of statistical dispersion, measuring the spread of NDVI values.

Coefficient of variation (CoV): CoV can be used to compare the amount of variation in different sets of sample data. NDVI CoV images were generated by computing for each pixel the standard deviation (STD) of the set of individual NDVI values and dividing this by the mean (M) of these values. This represents the dispersion of NDVI values relative to the mean value.

Temporal trends: The long-term trends of the indicators of biological productivity may be taken as indicators of land degradation (where the trend is declining) or land improvement (where the trend is increasing). A positive change in the value of a pixel-level CoV over time relates to increased dispersion of values, not increasing NDVI; similarly, a negative CoV dispersion – which is the case over nearly the whole country - means decreasing dispersion of NDVI around mean values, not decreasing NDVI.

The patterns and trends of all NDVI indicators for each pixel, determined by the slope of the linear regression equation, are depicted in Figures A1-7; their values are summarised in Table A1. No further analyses were made for these indicators except for the sum NDVI which is discussed in detail in the main text. It is recommended, however, that these maps should be considered in the field investigation - in particular the land use change during the study period (1981-2003).

Table A1. Statistics of NDVI indicators*

NDVI indicators	NDVI values			Pixels (%)		% NDVI change/year			Δ NDVI/year		
	min	max	mean	Pos.	Neg.	Pos.	Neg.	mean	Pos.	Neg.	mean
Minimum	0.116	0.285	0.222	32.5	67.5	0.535	0.694	-0.312	0.0009	0.0017	-0.0009
Maximum	0.366	0.580	0.463	66.8	33.2	0.508	0.270	0.228	0.0020	0.0014	0.0009
Max-Min	0.131	0.409	0.240	73.5	26.5	1.344	0.727	0.777	0.0029	0.0015	0.0017
Mean	0.272	0.387	0.334	54.7	45.3	0.330	0.284	0.040	0.0008	0.0010	0.00002
Sum	3.233	4.666	4.006	54.7	45.3	0.330	0.284	0.040	0.0107	0.0140	-0.0004
STD	0.041	0.127	0.076	76.4	23.6	1.467	0.726	0.927	0.0010	0.0005	0.0006
CoV	0.119	0.354	0.218	74.2	25.8	1.448	0.783	0.884	0.0032	0.0016	0.0021

*In the calculations of the min., max. and mean values of each NDVI indicator, an average value of the all pixels in the vegetated area, defined as areas with net primary productivity greater than 1 g C m^{-2} $year^{-1}$, were calculated. For example, *min.* value of the Maximum NDVI indicator: overlay statistic **minimum** of CELL STATISTIC in ArcMap was performed to extract minimum values of the time series annual Maximum NDVI for each pixel over the period (1981-2003), and the averaged **minimum** value of the maximum NDVI for all pixels was assigned as *min.* for the Maximum NDVI indicator; *max.* value of the Maximum NDVI indicator: overlay statistic **maximum** of CELL STATISTIC in ArcMap was performed to extract maximum values of the time series annual Maximum NDVI for each pixel over the period (1981-2003), and the averaged **maximum** value of the maximum NDVI for all pixels was assigned as *max.* for the Maximum NDVI indicator; *mean* value of the Maximum NDVI indicator: overlay statistic **mean** of CELL STATISTIC in ArcMap was performed to extract mean values of the time series annual Maximum NDVI for each pixel over the period (1981-2003), and the averaged **mean** value of the maximum NDVI for all pixels was assigned as *mean* for the Maximum NDVI indicator.

The rates of the positive and negative pixels were counted from the slope of the regression, i.e., positive slope (pos.) negative slope (neg.).

% NDVI change/year was calculated from the trend maps for each NDVI indicator: positive value (pos.) is the average of the all pixels with a positive trend; negative (neg.) is the average of the all pixels with a negative trend; mean value is the average of the all pixels; Δ NDVI/year is calculated the same as % NDVI change but from the absolute change maps.

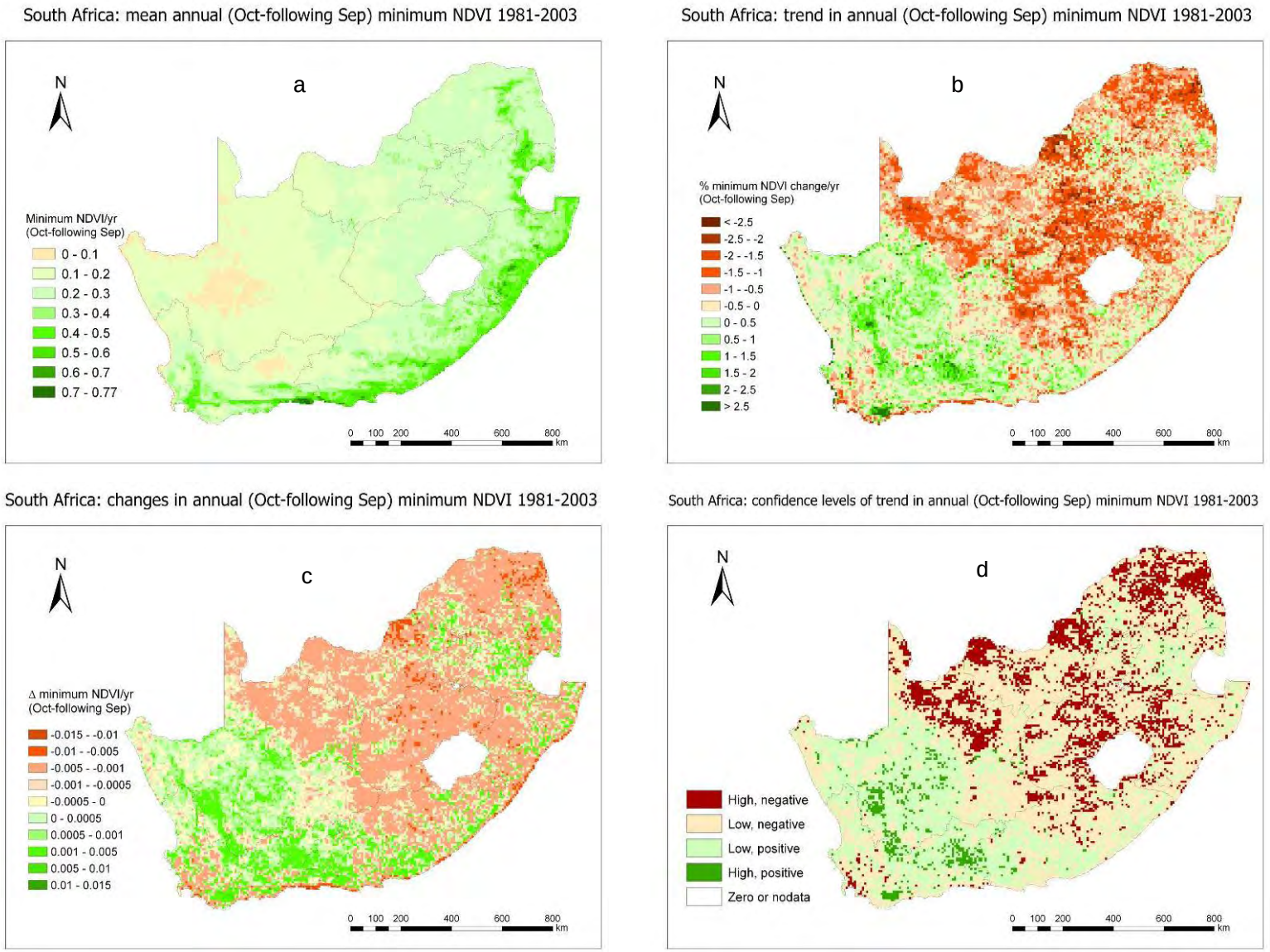

Figure A1. Annual minimum NDVI 1981-2003: pattern (a), trends (b – percentage, c - absolute) and confidence levels (d)
Years run from October through the following September

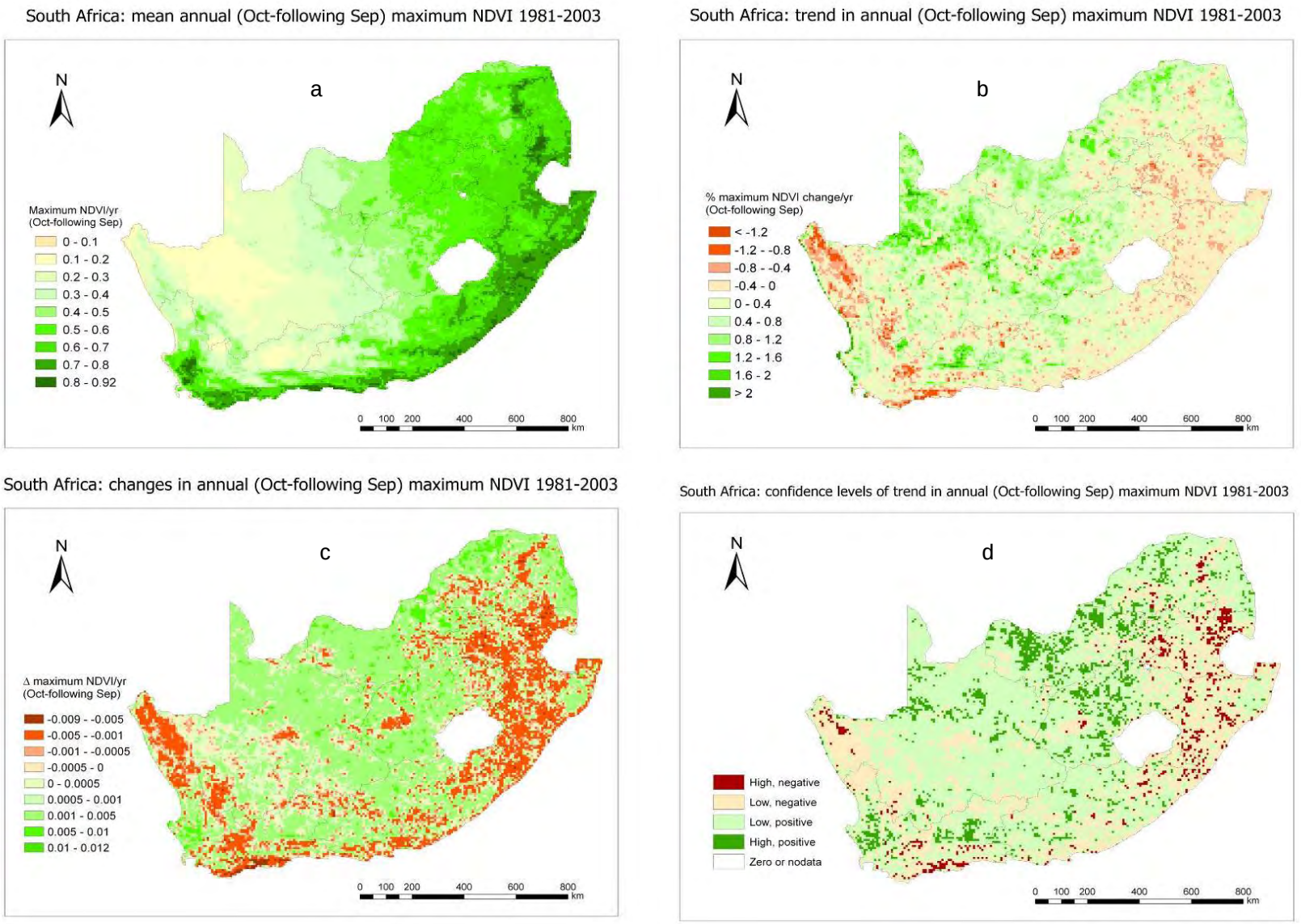

Figure A2. Annual maximum NDVI 1981-2003: pattern (a), trends (b - percentage, c - absolute) and confidence levels (d)
Years run from 1 October through the following September

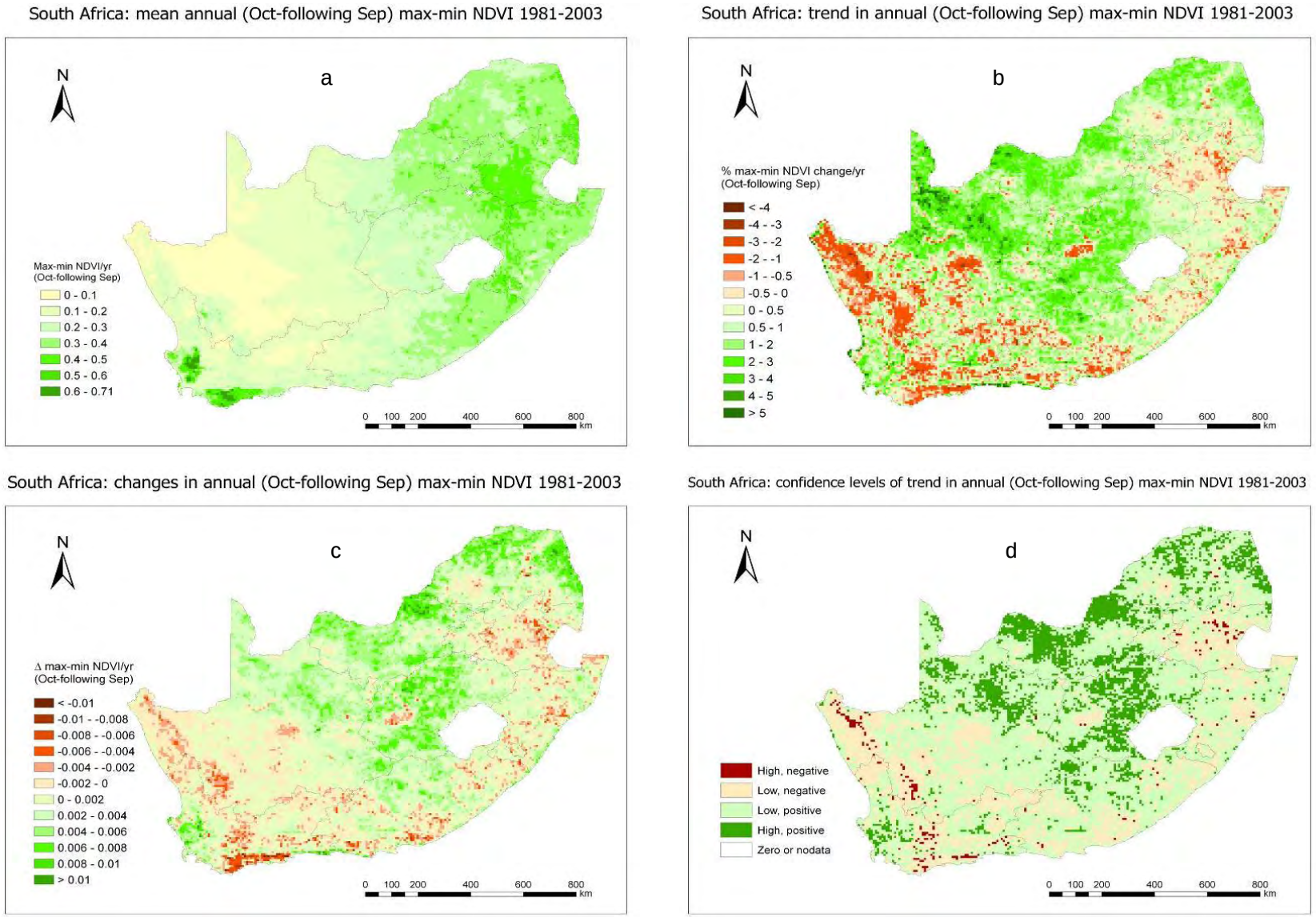

Figure A3. Annual max-min NDVI 1981-2003: pattern (a), trends (b - percentage, c - absolute) and confidence levels (d)
Years run from 1 October through the following September

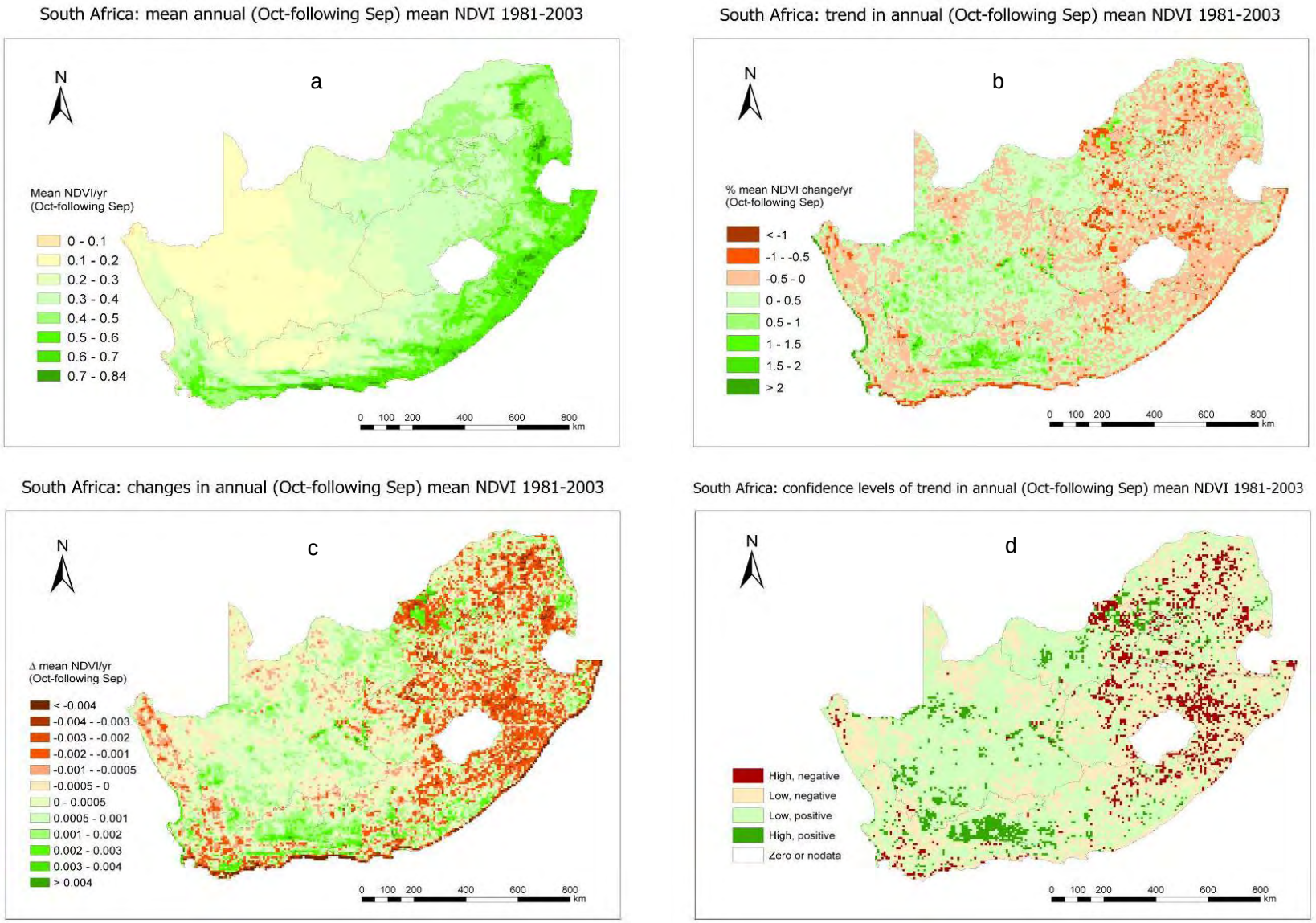

Figure A4. Annual mean NDVI 1981-2003: pattern (a), trends (b - percentage, c - absolute) and confidence levels (d)
Years run from 1 October through the following September

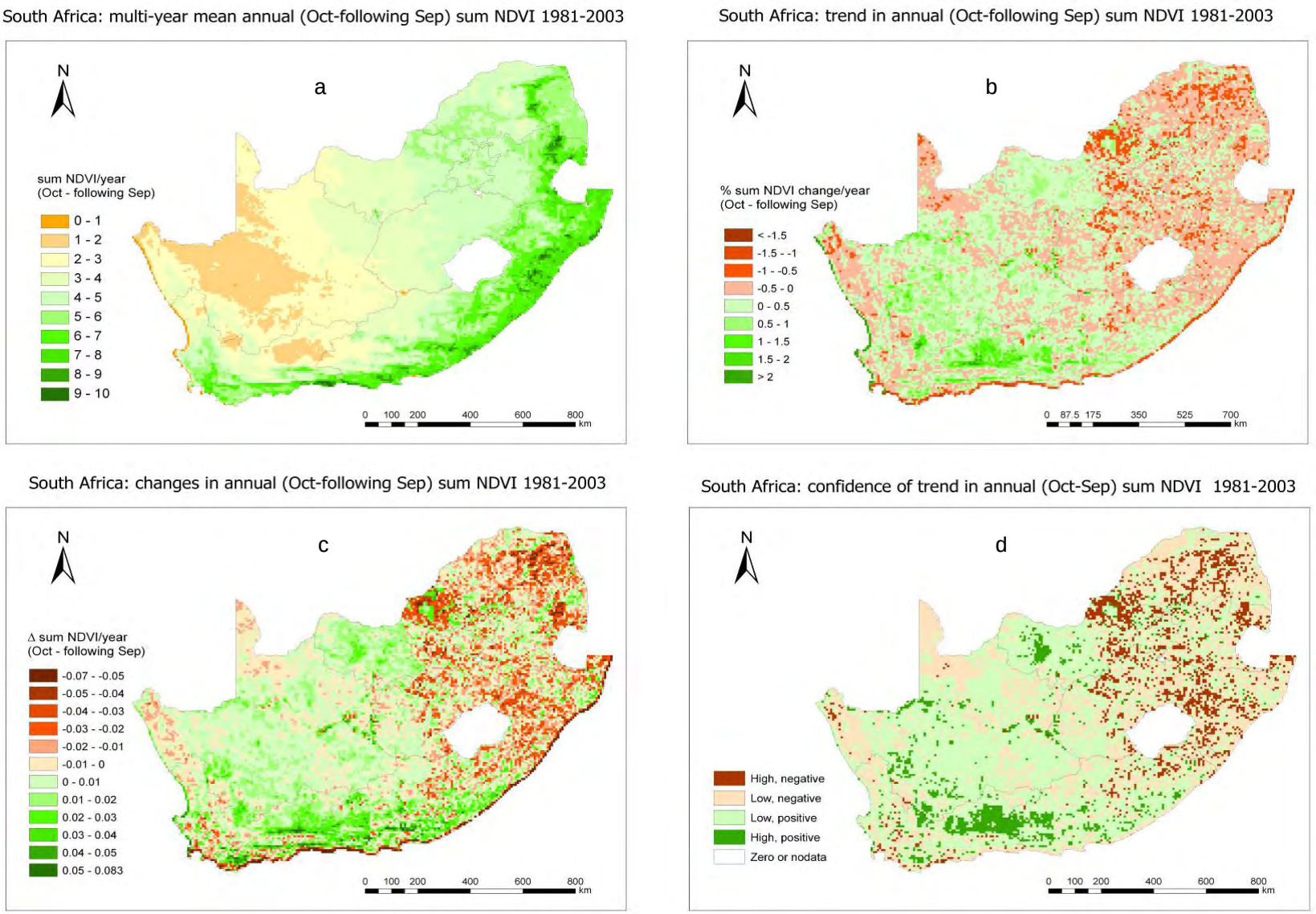

Figure A5. Annual sum NDVI 1981-2003: pattern (a), trends (b – percentage, c - absolute) and confidence levels (d)
Years run from 1 October through the following September

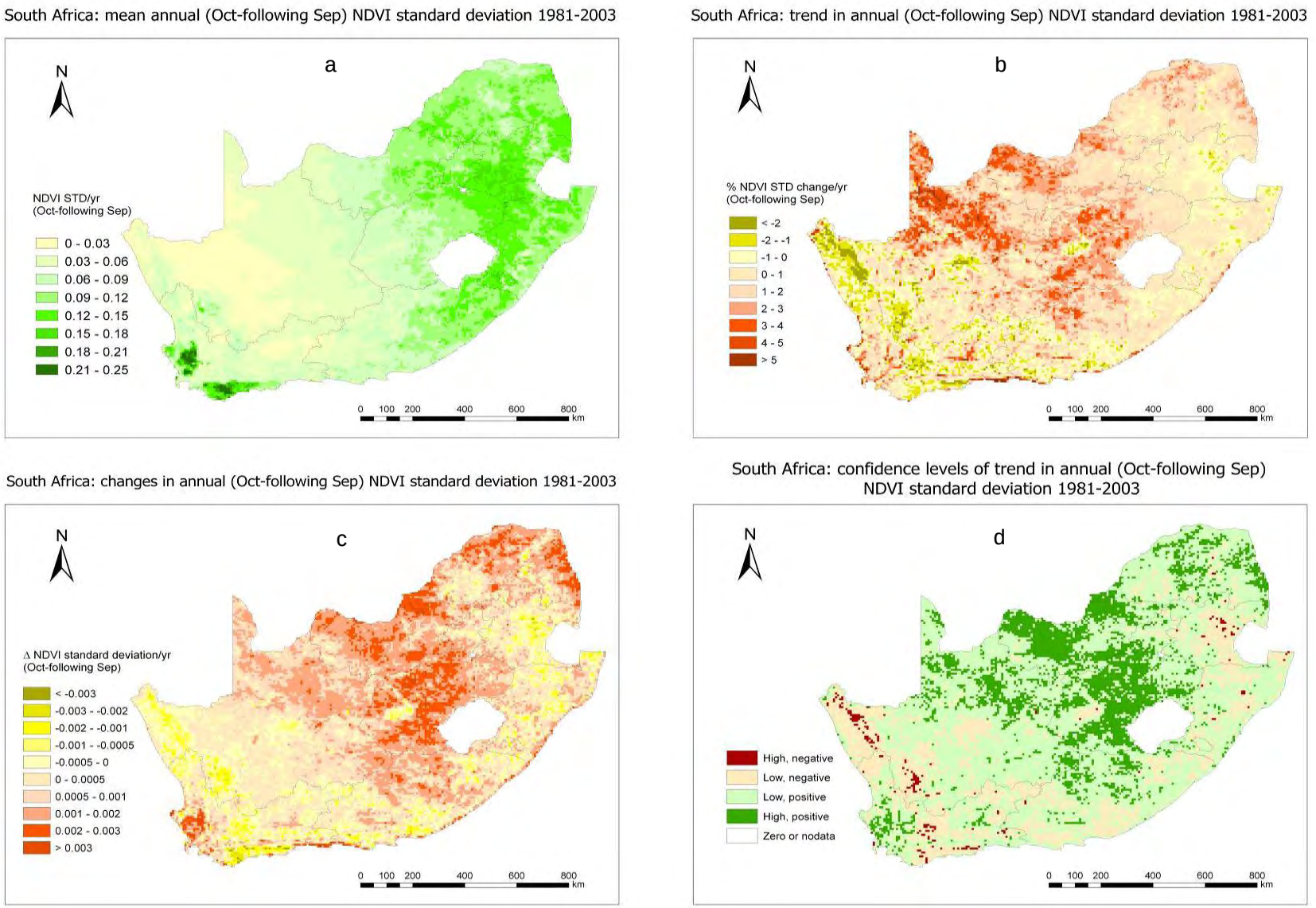

Figure A6. NDVI standard deviation 1981-2003: pattern (a), trends (b - percentage, c - absolute) and confidence levels (d)
Years run from 1 October through the following September

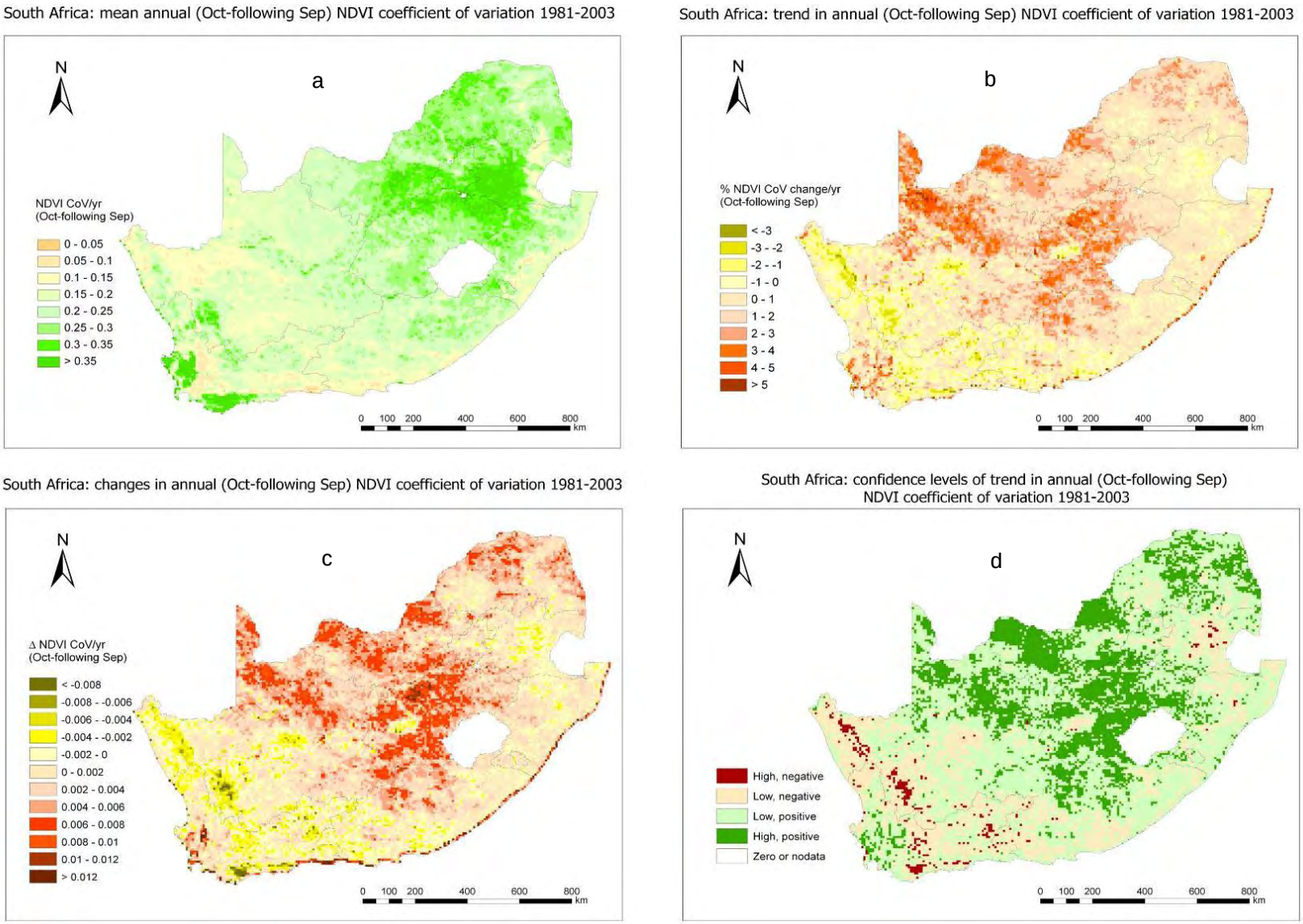

Figure A7. NDVI coefficient of variation 1981-2003: pattern (a), trends (b - percentage, c - absolute) and confidence levels (d)
Years run from 1 October through the following September

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- *To inform and educate - through the World Soil Museum, public information, discussion and publication*
- *As ICSU World Data Centre for Soils, to serve the scientific community as custodian of global soil information*
- *To undertake applied research on land and water resources.*