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# Land Degradation and Improvement in Tunisia

# 1. Identification by remote sensing

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LADA
Land Degradation Assessment in Drylands

ISRIC 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 degraded areas and areas where degradation has been arrested or reversed. This screening will be followed up in the LADA partner countries by field investigations to establish the situation on the ground.
2. **Land degradation and improvement is inferred from long-term trends of productivity when other factors that may be responsible (climate, soil, terrain and land use) are accounted for.** The remotely-sensed normalized difference vegetation index (NDVI) or greenness index is used as a proxy indicator of productivity; it may be translated to net primary productivity (NPP). Spatial patterns and temporal trends of climate – adjusted NPP are analysed for the period 1981-2003 at 8km resolution; land degradation is indicated by a declining trend and land improvement by an increasing trend.
3. **In Tunisia, over the period of 1981-2003, net primary productivity increased. Areas showing a decline in climate-adjusted NPP occupy 8 per cent of the country, mostly in the well-watered northeast.** These degrading areas suffered an average loss of NPP of 14 kgC/ha/year.
4. **Almost half of the degrading area is scrubland; almost one third of the degrading land is cropland, 30 per cent of the arable; 12 per cent is forest.**
5. **About 1.5 million people (15 per cent of the Tunisian population) live in the areas afflicted by land degradation.** There are no clear correlations between rural population density and land degradation, or with poverty. More rigorous analysis is needed to tease out the underlying social and economic drivers.
6. **Nine per cent of the country shows an increase in climate-adjusted net primary productivity, mostly in the north**: Of the improving area, 7 per cent is cropland, 87 per cent is under scrub and herbaceous cover, and 3 per cent under forest.

**Keywords:** land degradation/improvement, remote sensing, NDVI, rain-use efficiency, net primary productivity, land use/cover, Tunisia

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# Abbreviations

| | |
|---|---|
| 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 Phenomenon |
| FAO | Food and Agriculture Organization of the United Nations, Rome |
| GIMMS | The Global Inventory Modelling and Mapping Studies |
| GLADA | Global Assessment of Land Degradation and Improvement |
| JRC | Joint Research Centre, European Commission, 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 |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| NASA | National Aeronautics and Space Administration |
| NDVI | Normalized Difference Vegetation Index |
| NPP | Net Primary Productivity |
| RESTREND | Residual Trend of sum NDVI |
| RUE | Rain-Use Efficiency |
| SOTER | Soil and Terrain Database |
| SPOT | Système Pour l'Observation de la Terre |
| SPSS | Statistical Package for the Social Sciences software |
| SRTM | Shuttle Radar Topography Mission |
| UNCED | United Nations Conference on Environment and Development |
| UNEP | United Nations Environment Programme, Nairobi, Kenya |
| VASClimO | Variability Analyses of Surface Climate Observations |

# 1 Introduction

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 Convention on Biodiversity and Climate Change, and the Millennium Goals (UNCED 1992, UNEP 2007).

Quantitative, up-to-date information is needed to support policies for food and water security, environment, and development. The only 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), this new the *Global Assessment of Land Degradation and Improvement* (GLADA) maps degradation and improvement according to change in net primary productivity (NPP, the rate of removal of carbon dioxide from the atmosphere and its conversion to biomass).

Satellite measurements of the normalised difference vegetation index (NDVI or greenness index) for the period 1981-2003 are used as a proxy for NPP. They 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 only provide indicators: 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 variation in rainfall and temperature), 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 and terrain 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 the trend of residuals 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; in addition the comparable RESTREND values are presented.

The pattern of land degradation is further explored by comparisons with soil and terrain, land cover, and socio-economic data. In the LADA program, areas identified by this first screening will be validated and characterized in the field by national teams.

# 2 Context and methods

## 2.1 LADA partner country: Tunisia

Tunisia is experiencing a clash between rapid development and the need to conserve its natural resources and environment (Baban and others 1999). Environmental issues include land degradation, sedimentation and loss of biological diversity driven by industrialization, urbanization, population growth and climatic change. Climate variability, especially recurrent drought, has always been a constraint on land use and productivity. It is exacerbated by land degradation in the shape of soil erosion and salinization, driven by overgrazing and agricultural expansion that destroys the land's protective vegetation cover by (Woodward 1995, Lahlou 1996, Woodward and Foster 1997). Land degradation means a loss of farmland and water resources, increased sediment loads in the rivers, siltation of reservoirs and a falling water table - threatening food and water security and economic development, and driving a flight of people from the land.

Demographic and economic pressures have led to cropping practices that sap soil fertility and accelerate soil erosion, such as cereal monoculture and the expansion of rain-fed crops into the best rangeland - so more animals are grazing fewer hectares. Most of the country is rangeland; livestock are an important source of milk and protein, the collection of fuel wood and medicinal plants is also important. There is a perception that rangelands are being degraded by overgrazing in response to human population pressure and breakdown of traditional management.

## 2.2 Data

### *2.2.1 NDVI and net primary productivity*

The NDVI data 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, and Landsat ETM+ (Tucker and others 2005, Brown and others 2006). GIMMS data from July 1981 to December 2003 were used.

To provide 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), the dataset 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 these data are reliable at the regional scale (Zhao and others 2005, 2006).

### 2.2.2 Climatic data

The VASClimO 1.1 dataset comprises the most complete monthly precipitation data for 1951-2000, compiled on the basis of long, quality-controlled station records, gridded at resolution of 0.5° (Beck and others 2005); monthly rainfall data since January 1981 were supplemented by the GPCC full re-analysis product (Schneider and others 2008) to produce rainfall values matching 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° resolution, were used to calculate the aridity index and energy-use efficiency.

### 2.2.3 Soil and terrain

A 1:1million soil and terrain dataset for Tunisia has been compiled for analysis of land degradation in relation to soils and terrain (Engelen and others 2008).

### 2.2.4 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 mask the urban area. Sub-national rates of infant mortality and child underweight status and the gridded population for 2005 at 2.5 arc-minutes resolution (CIESIN 2005) were compared with indices of land degradation.

### 2.2.5 Land cover and land use

Land cover data (Figure 1) have been generalised from Land Cover 2000 global data (JRC 2003). Similarly, Land use systems of the World (FAO 2008) have been derived for Tunisia and used for preliminary comparison with NPP trends.

### 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.

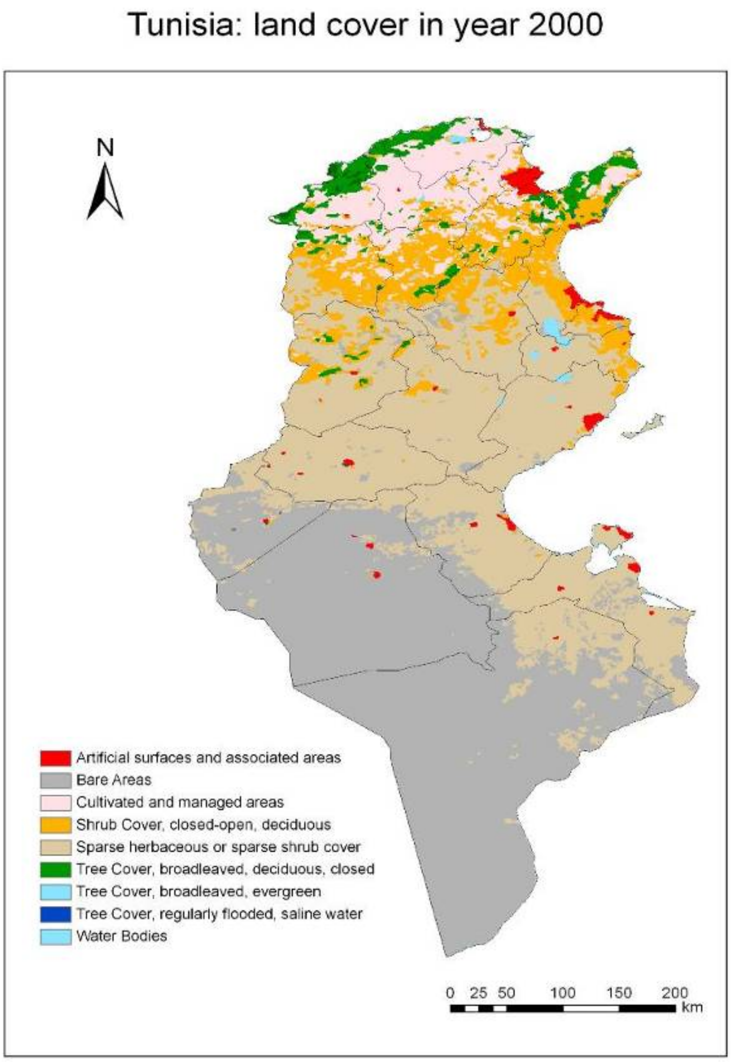


**Figure 1**. Main land cover types (JRC 2003)

## 2.3 Analysis

Degrading and improving areas are identified by a sequence of analyses of the remotely-sense data:

1. Simple NDVI indicators: NDVI minimum, maximum, maximum-minimum, mean, sum, standard deviation and coefficient of variation are computed for the calendar year. Their trends are analysed over the 23-year period of the GIMMS data. Each of these indicators has biological meaning (Appendix 2);
2. The annual sum NDVI, the annual aggregate of greenness is chosen as the standard proxy for annual biomass productivity. NDVI is translated to NPP by correlation with MODIS NPP data; trends are calculated by linear regression;

3. To distinguish between declining productivity caused by land degradation and declining productivity caused by other factors, false alarms must be eliminated. Rainfall variability and irrigation have been accounted for by:
    a. Identifying where there is a positive relationship between NDVI and rainfall, i.e. where rainfall determines productivity;
    b. Where rainfall determines productivity, RUE has been considered: where NDVI declined but RUE increased, we may attribute declining productivity to declining rainfall; those areas are masked (urban areas are also masked);
    c. For the remaining areas with a positive relationship between NDVI and rainfall but declining RUE, and also for all areas where there is a negative relationship between NDVI and rainfall, i.e. where rainfall does not determine productivity, 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. To take account of the significant lengthening and warming of the growing season at high latitudes and altitudes, energy-use efficiency – ratio of annual sum NDVI to accumulated temperature is calculated and overlaid on RUE-adjusted NDVI to calculate climate-adjusted NDVI;
6. The indices of land degradation and improvement are compared with land cover, land use, aridity, rural population density and indices of poverty.

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

The next phase of investigations will investigate the relationships between degradation and soils and terrain. In addition, manual interpretation 30m-resolution Landsat data will be employed to characterisation of *hot spots* of land degradation and *bright spots* of improvement and 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 *hot spots* and *bright spots* will be undertaken by national teams within the LADA program.

# 3 Results

The spatial patterns and temporal trends of several 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 according to rainfall cycles. In Tunisia over the period of 1981-2003, biomass productivity increased overall (Figure 2, Table A1).

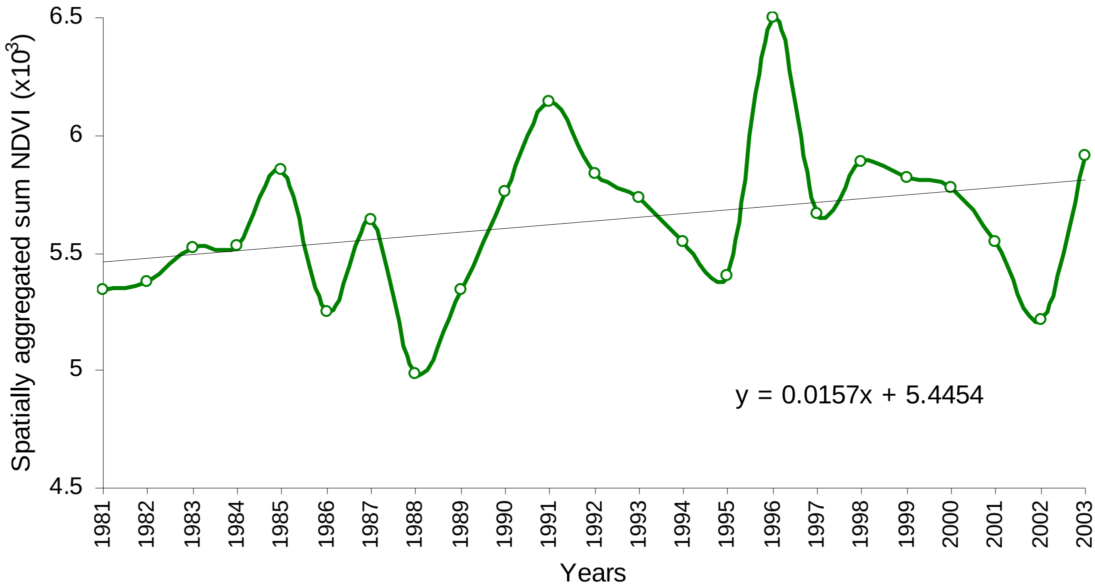


**Figure 2. Spatially aggregated annual sum NDVI 1981-2003, $p<0.05$**

Figure 3 depicts the pattern and trends of annual sum NDVI for each pixel, determined by the slope of the linear regression equation: the trends increased across 76 per cent of the country and decreased over 24 per cent; confidence levels refer to T-test values.

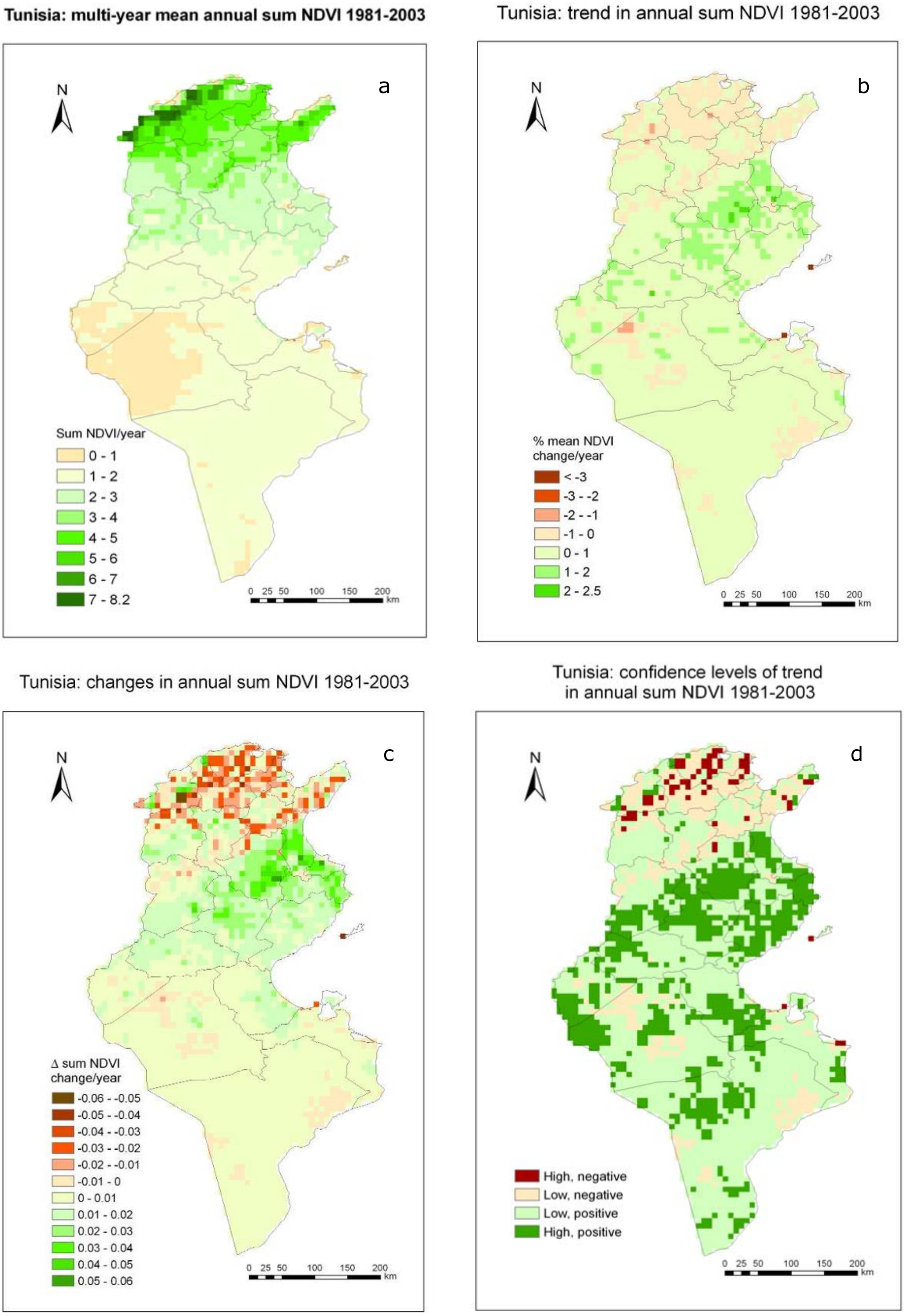


**Figure 3. Annual sum NDVI 1981-2003: mean (a) and trends (b – percentage, c – absolute, d - confidence levels)**

## 3.2 Spatial patterns of biomass and rainfall

Biomass productivity varies according to rainfall, stage of growth and changes in land use, as well as land quality. Annual biomass productivity (represented by sum NDVI in Figure 3a) essentially follows annual rainfall (Figure 5a) which has fluctuated both cyclically (Figure 4) and across the country (Figure 5b, c). Statistics show a high correlation between NDVI and annual rainfall:

$$NDVI_{ann.\ sum} = 0.0092 * \text{Rainfall [mm yr}^{-1}] - 0.78 \quad [1]$$

($r^2$ = 0.76, n=1 470)

The standard error in the regression model [1] is: slope (0.0092) ± $8.5 \times 10^{-5}$; intercept (-0.78) ± 0.007.

For Tunisia as a whole, rainfall slightly increased over the study period, at an average of 1.6mm/yr; increasing over 82 per cent of the country (with an annual rate of 2.3mm) and decreasing over 18 per cent (average rate of 1.7mm/yr) in particular across Bizerte, Jendoba, Beja and L' ariana.

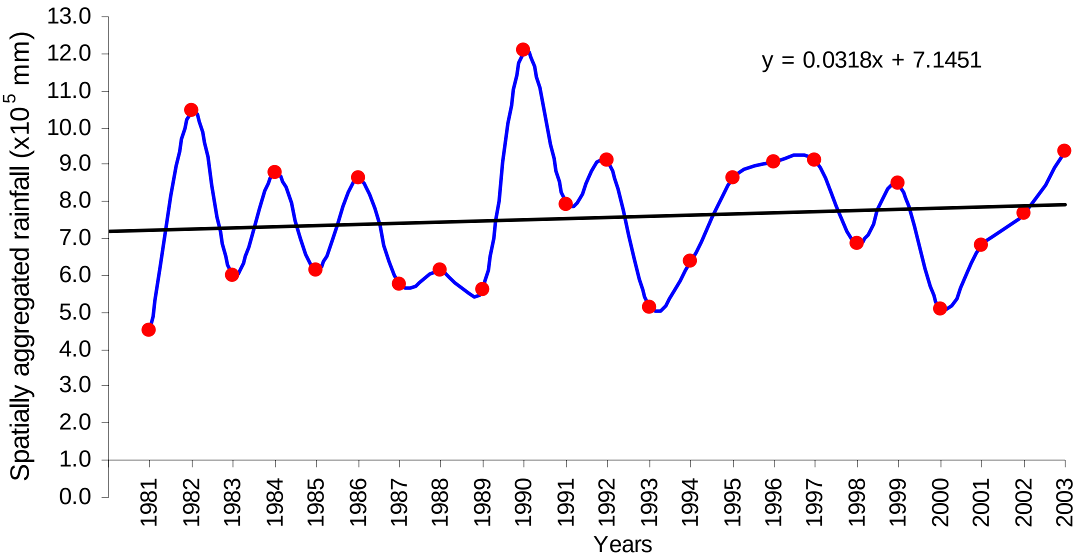


**Figure 4. Spatially aggregated annual rainfall 1981-2003: P<0.05**

Over the same period, biomass productivity also increased overall. However, contrasting regional trends mean that the correlation of biomass productivity and rainfall is weak for the country as a whole (Figure 6).

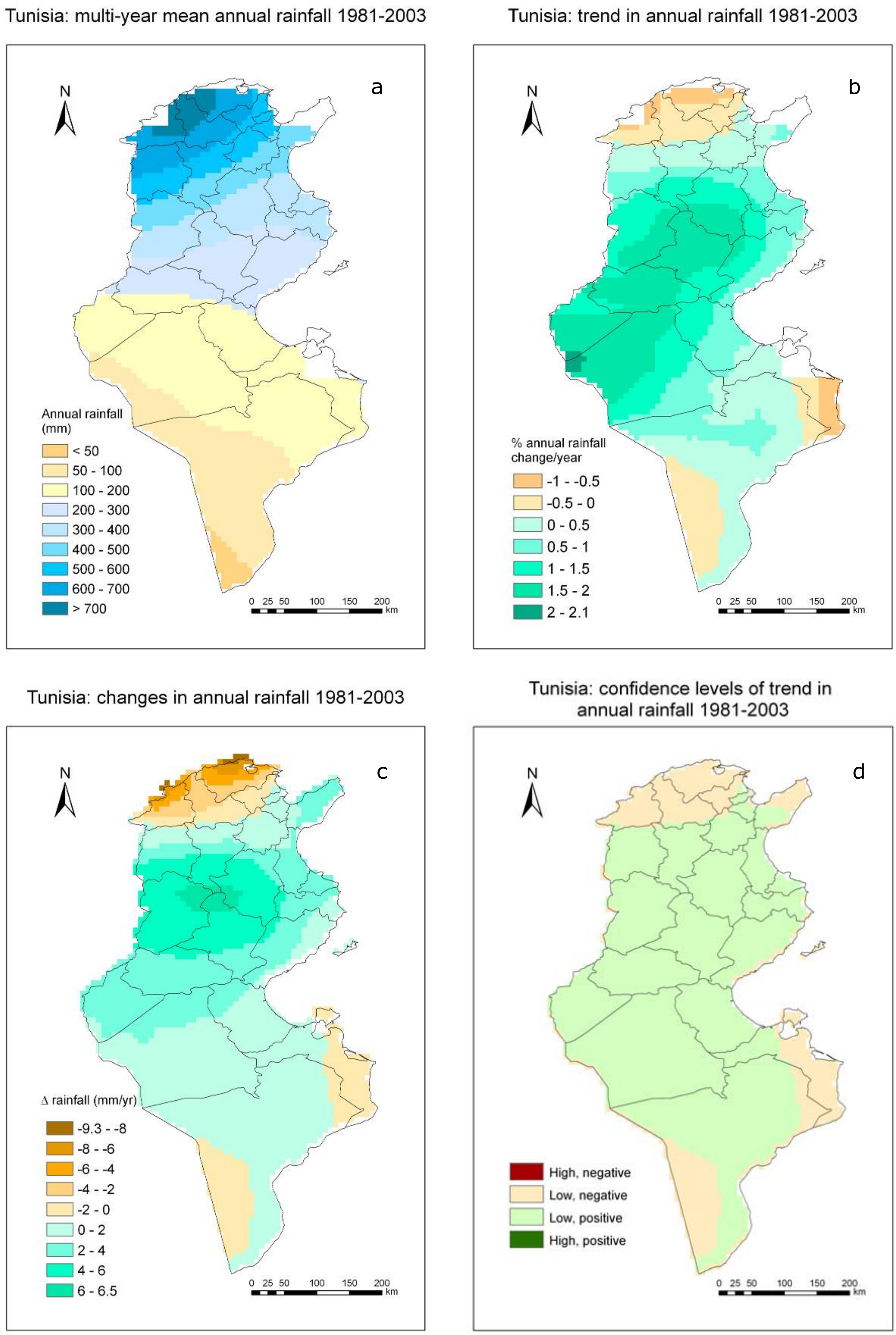


**Figure 5. Annual rainfall 1981-2003: multi-year mean (a) and trends (b – percentage change, c – absolute change, d - confidence levels)**

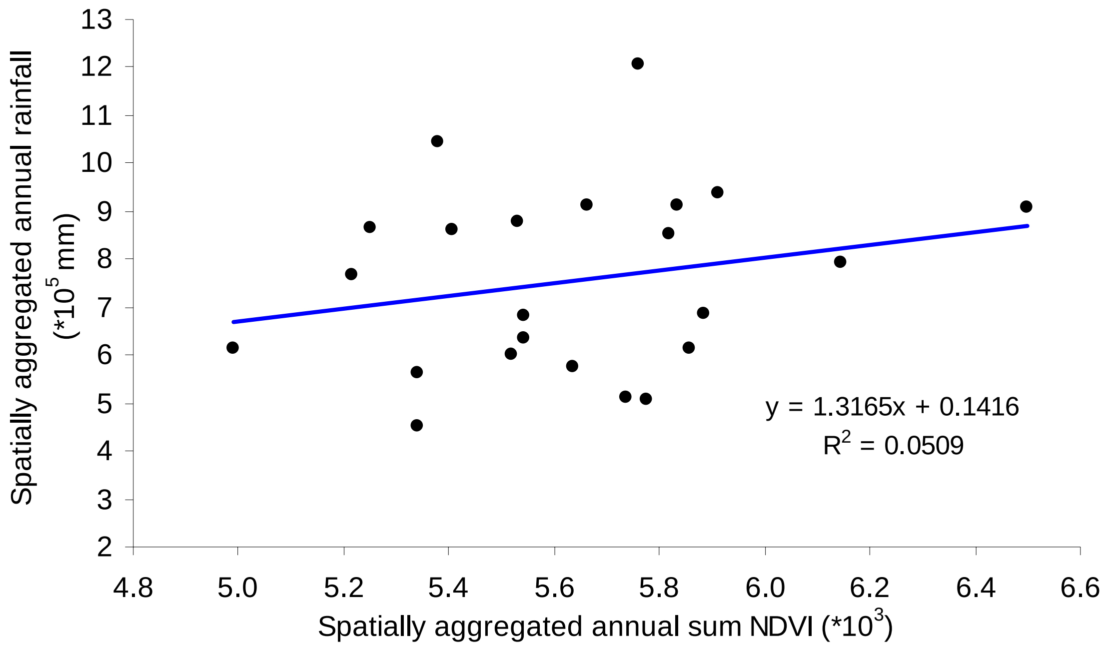


**Figure 6. Relationship between annual sum NDV and annual rainfall (all pixels)**
Each dot represents one year, $p<0.05$

## 3.3 Rain-use efficiency

Allowance may be made for the effects of variable rainfall on biomass productivity by considering rain-use efficiency (RUE, production per unit of rainfall). RUE may fluctuate dramatically in the short term; often, there is a sharp decline in a wet year and we may assume that the vegetation, whether cultivated or semi-natural, cannot make immediate 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). RUE 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 measurements of net primary productivity, which are not easy to obtain. For Tunisia, RUE was calculated as the ratio of annual sum NDVI and station-observed annual rainfall.

Figure 7 shows the spatial pattern and temporal trend of RUE over 1981-2003: RUE decreased over 88 per cent of the country, mostly across the dry south and centre and increased over 12 per cent, with a statistically significant increase in some small areas in the Mediterranean coastal belt. Confidence levels are assessed by the T-test.

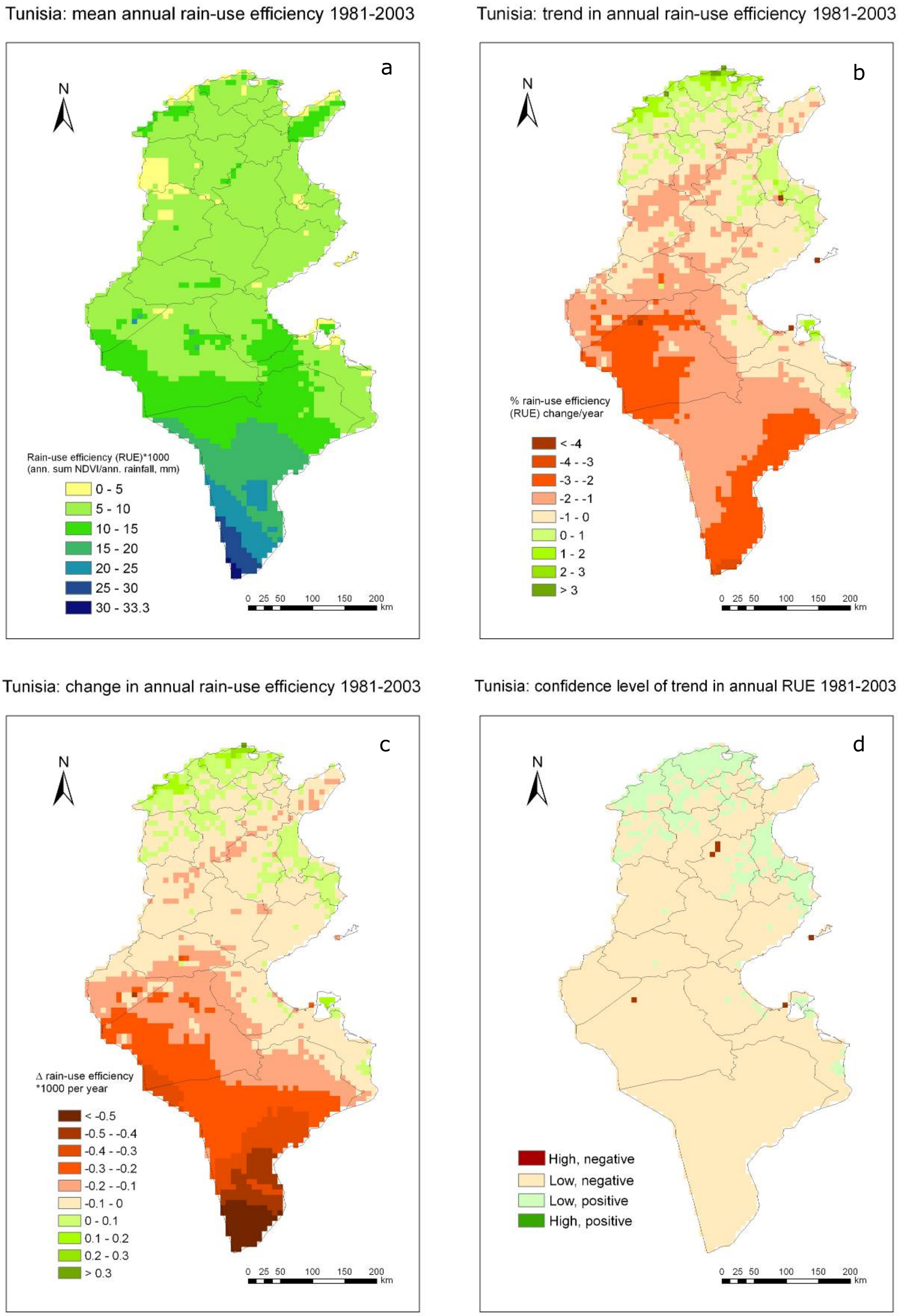


**Figure 7. Rain-use efficiency 1981-2003: mean (a) and trends (b – percentage changes, c – absolute changes, d - confidence levels)**

## 3.4 RESTREND

Countrywide, there is a significant negative correlation between RUE and rainfall (r=-0.57, n=2 816) so that RUE, used in isolation, says as much about rainfall variability as about land degradation. To avoid the correlations between RUE and rainfall, Wessels and others (2007) suggest the alternative use of the residuals of NDVI to distinguish land degradation from the effects of rainfall variability. Following their general procedure, we have correlated for each pixel annual sum NDVI and annual rainfall. 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 (RESTREND) 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 may indicate land degradation and a positive RESTREND improvement, but the spatial distribution is different from RUE. Overall, RESTREND patterns are remarkably close to sum NDVI but of lesser amplitude (Figure 3c), see Section 3.9.

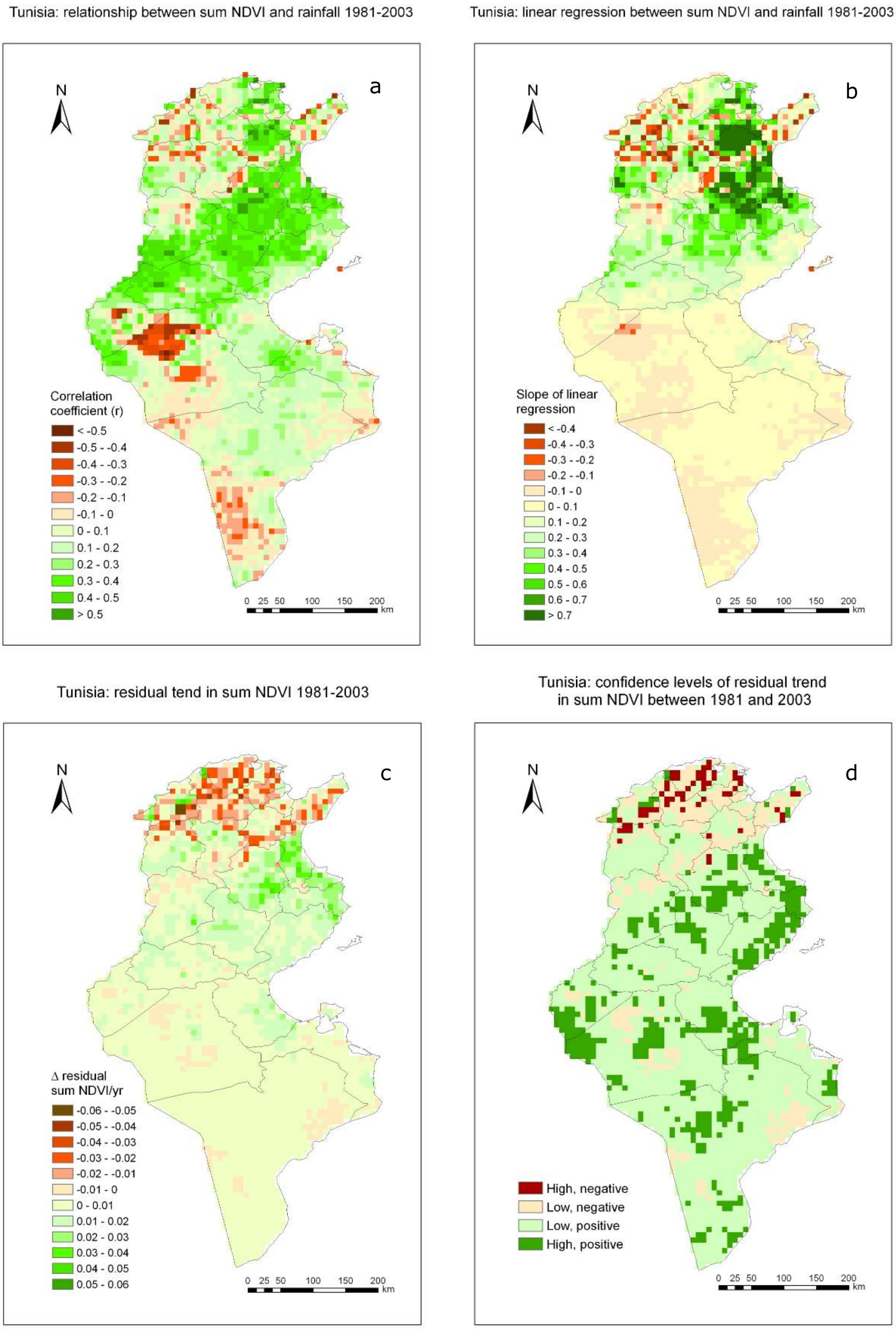


**Figure 8. Residual trend of sum NDVI (RESTREND) 1981-2003**
(a) Correlation coefficient between sum NDVI and annual rainfall; (b) Slope of linear regression between sum NDVI and rainfall; (c), RESTREND; (d) Confidence levels of RESTREND

## 3.5 Net primary productivity

It is hard to visualise the degree of land degradation and improvement from NDVI. For a quantitative estimate, 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 MODIS (at 1km resolution from the year 2000). Figure 9a shows four-year (2000-2003) mean annual MODIS NPP at 1-km resolution; the pattern is similar to the GIMMS annual sum NDVI (Figure 3a) but at finer detail. GIMMS NDVI data were translated to NPP by correlation with MODIS 8-day NPP values for the overlapping period: 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. Correlation between the two data sets is high:

$$NPP_{MOD17}\ [\text{tonneC ha}^{-1}\ \text{year}^{-1}] = 0.7754 * NDVI_{sum} - 0.4131 \qquad [2]$$

(r = 0.75, n = 1 533, $P<0.001$)

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

The standard error in the regression model [2] is: slope (0.7754) ± 0.0354; intercept (-0.4131) ± 0.1055.

Correlation between the two raster data for all land cover types is very high globally (Bai and others 2008) and also high for Tunisia so the MOD17A3 NPP product has been used to convert the NDVI values to NPP. The translation is approximate.

Changes in NPP over the period 1981-2003 are mapped in Figure 9b and c; the confidence level (Figure 9d) refers to the T-test (Appendix 1). The statistics were applied to the vegetated area - defined as areas with NPP greater than 1 g C $m^{-2}$ $year^{-1}$; the vegetated land is about 38 per cent of the country. During the period, net primary productivity increased overall (Table 1).

**Table 1. Changes in net primary productivity 1981-2003**

| | *Positive* | *Negative* | *Average* |
|---|---|---|---|
| Land area (pixels, %) | 76 | 24 | |
| % NPP change/year (tonneC $ha^{-1}$ $year^{-1}$) | 1.23 | 0.53 | 0.66 |
| Δ NPP (kgC $ha^{-1}$ $year^{-1}$) | 10.60 | 10.01 | 3.86 |

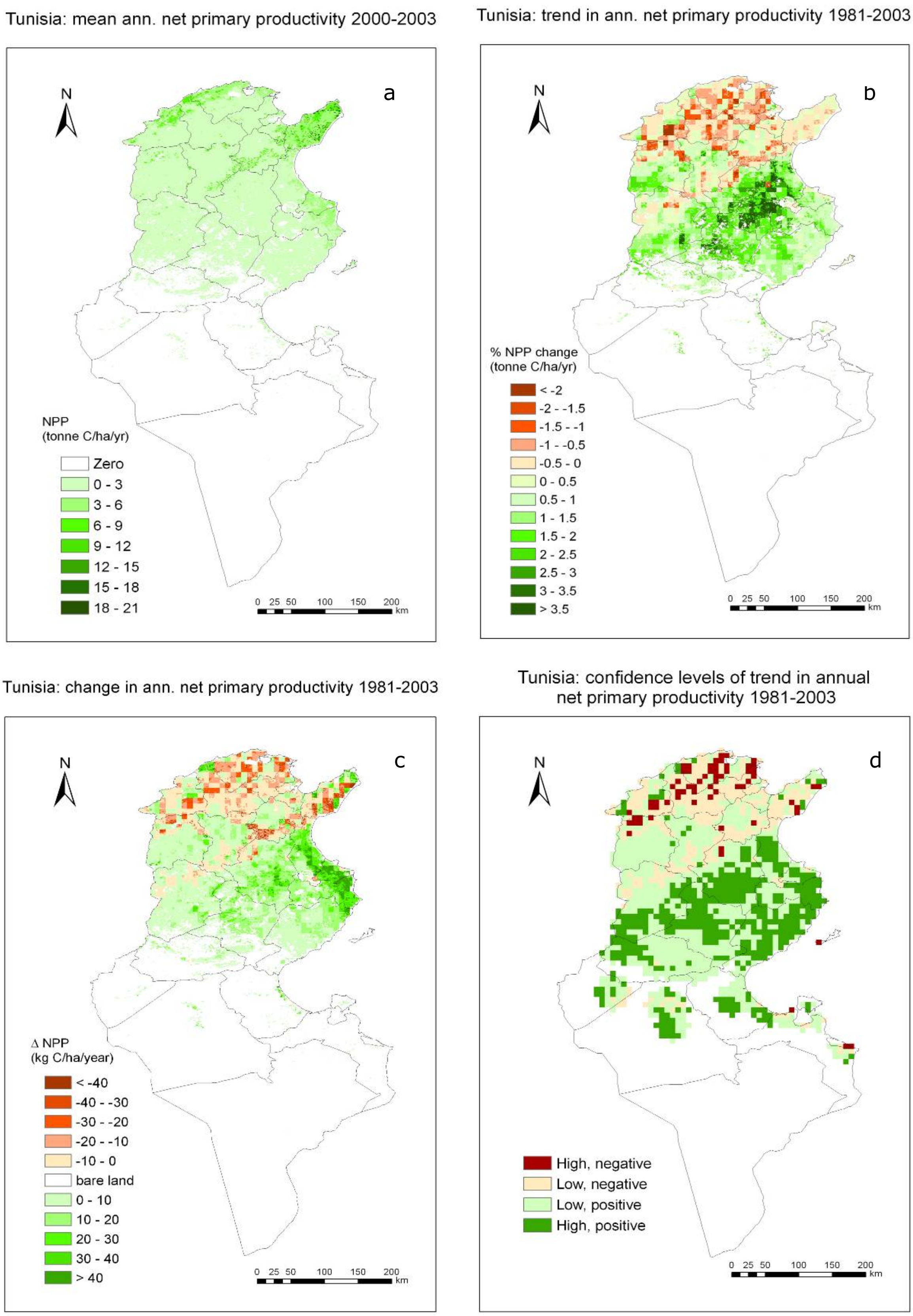


**Figure 9. Changes in NPP 1981-2003: mean (a) and trends (b – percentage change, c – absolute change, d – confidence level)**

## 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 accounted for 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.

Figure 10 depicts the negative trend of RUE-adjusted NDVI 1981-2003. Degrading areas make up rather less than 8 per cent of the country, mostly on the steep north easterly extension of the Mountains of Tebessa to the Mabuim Peninsula, and the lowlands to the north.

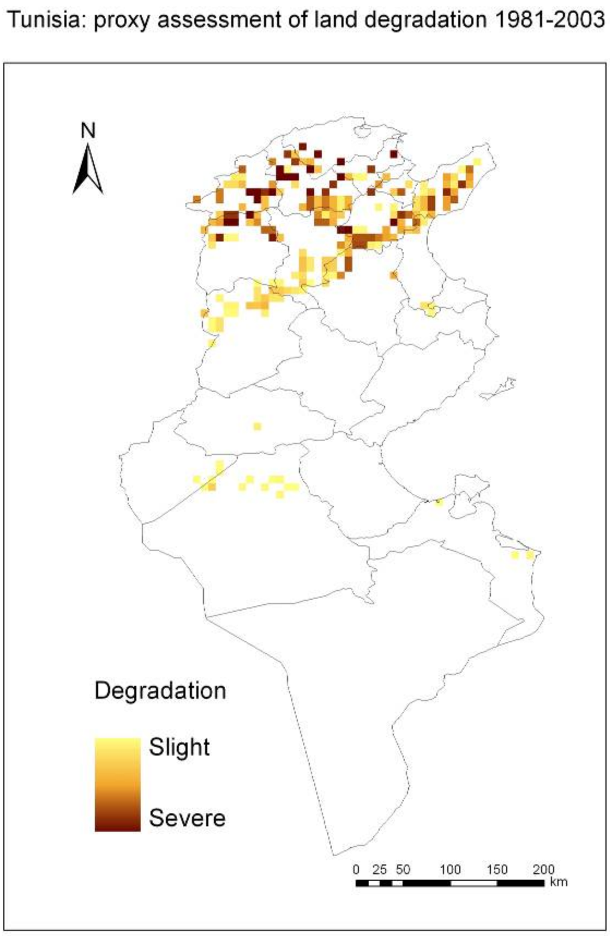


**Figure 10. Negative trend in combined index of NPP and RUE, 1981-2003**

***Quantitative estimation:*** To estimate the decline in productivity in quantitative terms, we have calculated loss of NPP, relative to the average, by translating RUE-adjusted NDVI to RUE-adjusted NPP using the relationship between GIMMS and MODIS data for the overlapping years 2000-2003 (Figure 11, Table 2).

**Table 2. Tunisia and World: NPP loss in degrading land 1981-2003**

| | *Degrading land ($km^2$)* | *% territory* | *% global degrading land* | *NPP loss (kg C/ha/yr)* | *Total NPP loss (Tonne C/23yr)* |
|---|---|---|---|---|---|
| Tunisia | 12 476 | 7.6 | 0.04 | 13.9 | 398 423 |
| World | 35 058 104 | 23.5 | 100 | 11.8 | 955 221 419 |

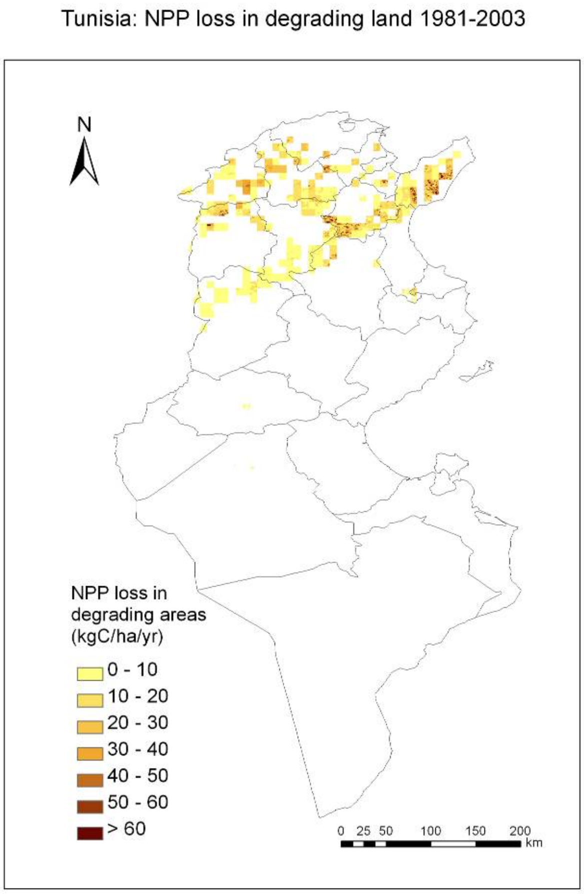


**Figure 11. NPP loss in the degrading areas 1981-2003**

***Comparison between RUE-adjusted NDVI and RESTREND:*** For Tunisia, the two indicators of land degradation show very similar patterns (compare Figures 10 and 8c) and their statistical confidence levels are comparable, cf Section 3.9.
Negative RESTREND encompasses a somewhat larger area than negative RUE-adjusted NDVI.

***Land use change:*** As with rainfall variability, land use change may also generate false alarms. For instance, 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. However, this will be undertaken manually for the potential *hot spots* of land degradation identified in this analysis and presented in a later report.

## 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 12). These areas account for about 9 per cent of the country with the greatest concentration in the Sousse coastal plain. Figure 13 shows the gain in NPP in those areas.

Apart from the areas showing clear indications of land degradation or improvement, the remaining vegetated land (21 per cent of the country) shows no clear direction.

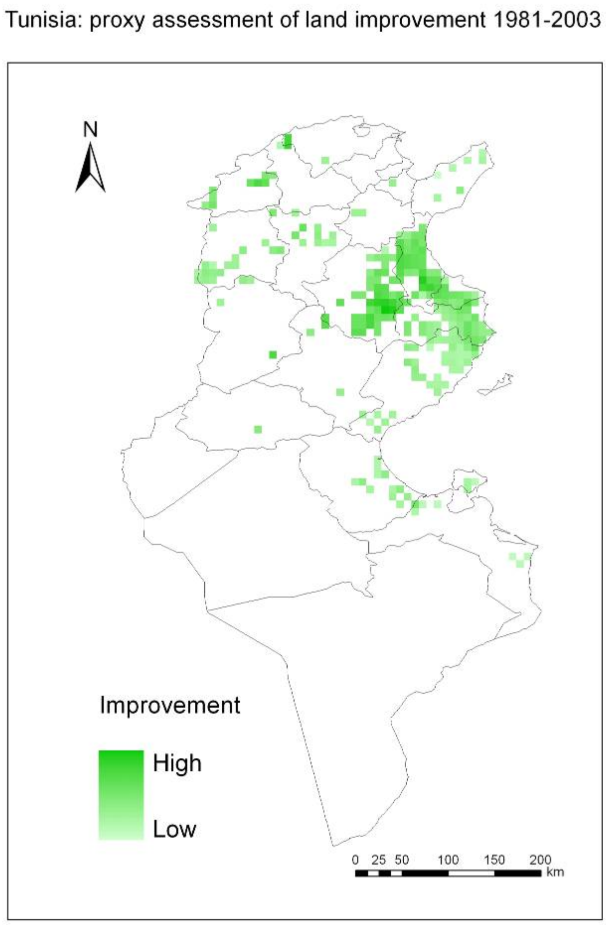


**Figure 12. Areas of increasing NPP, RUE and EUE, 1981-2003**

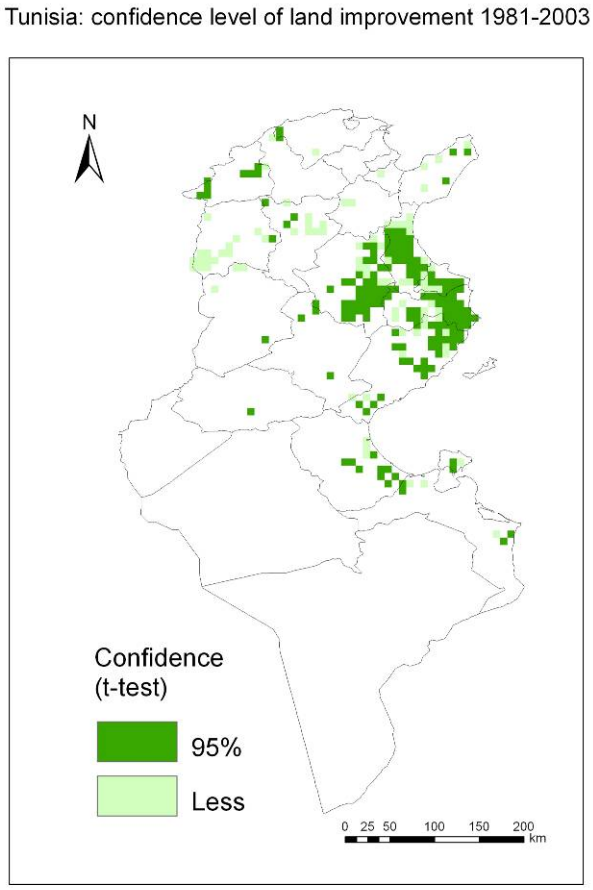


**Figure 13. Confidence levels of positive climate-adjusted NDVI, 1981-2003**

## 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 sealing of the land surface, it is degradation according to our criterion of partial loss of ecosystem function.

The CIESIN Global Rural Urban Mapping Project shows 6.2 per cent of the land area as urban. This area is masked in the maps, which leads to a reduction of 12 per cent in the area of identified degrading land, and a reduction of 27 per cent for the improving land.

## 3.9 Comparison of indicators

Annual sum NDVI, i.e. annually accumulated greenness, is our standard indicator of land degradation and improvement. Rain-use efficiency, RUE-adjusted NDVI and RESTREND are different ways of eliminating false alarms caused by rainfall variability (cf Sections 3.3 and 3.4, respectively).

Countrywide, the patterns of the trends in sum NDVI and RESTREND are almost identical (Table 3): about 11 per cent of land area shows negative change in both sum NDVI and RESTREND, 40 per cent shows positive trend in both indictors, 47 per cent no change and only 2 per cent gives a mixed signal - either positive sum NDVI and negative RESTREND, or vice versa.

If we take negative RUE-adjusted NDVI as the primary definition of degrading areas, then 96 per cent of these areas are also degrading in terms of *both* unadjusted NDVI and RESTREND. Taking a positive trend of RUE-adjusted NDVI as the primary definition of improving land, the whole of this area is are also positive in terms of both unadjusted NDVI and RESTREND.

Comparing RUE with RESTREND, 9 per cent of the land area shows negative trend in both RUE and RESTREND, 8 per cent shows positive trend in both indicators and 48 per cent no change. But we get mixed signals from 35 per cent: either positive RUE and negative RESTREND, or vice versa. If we again take RUE-adjusted NDVI as the primary definition of degrading areas, then 84 per cent shows negative trend in both RUE and RESTREND, and 55 per cent of the improving area shows positive trend in both RUE and RESTREND.

**Table 3. Comparison of indicators, 1981-2003**

| *Indicators* | *Total pixel* (%) | *Negative trend* (%) | *Positive trend* (%) | *No change* (%) | *Mixed* (%) |
|---|---|---|---|---|---|
| Annual sum NDVI | 100 | 12.4 | 40.4 | 47.2 | 0.0 |
| RESTREND[1] | 100 | 11.6 | 40.6 | 47.7 | 0.0 |
| Sum NDVI ∩ RESTREND | 100 | 11.1 | 39.9 | 47.1 | 2.0 |
| Sum NDVI ∩ RESTREND within LD[2] | | **95.5** | | | |
| Sum NDVI ∩ RESTREND within LI[3] | | | **100.0** | | |
| RUE | 100 | 41.7 | 11.3 | 46.9 | 0.0 |
| RUE ∩ RESTREND | 100 | 9.0 | 8.2 | 47.7 | 35.1 |
| RUE ∩ RESTREND within LD | | **84.1** | | | |
| RUE ∩ RESTREND within LI | | | **55.0** | | |

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

## 3.10 Analysis of degrading and improving areas

### 3.10.1 Association with land cover and land use

Table 4 compares degrading and improving areas with land cover (Figure 1): 32 per cent of the degrading area is cropland (comprising 30 per cent of the arable); 48 per cent is grassland and scrub (codes 12 and 14). Of the improving areas, 7 per cent is cropland (7 per cent of all cropland); 86 per cent is scrub and grassland; and 3 per cent is forest.

**Table 4. Degrading and improving land by land cover**

| Code | Land cover | Total pixels (TP)[1] | Degrading pixels (DP)[2] | DP/TP | P/TDP[3] | Improving pixels (IP) | IP/TP | IP/TIP[4] |
|---|---|---|---|---|---|---|---|---|
| | | | | (%) | (%) | | (%) | (%) |
| 1 | Tree cover, broadleaved evergreen | 329 | 78 | 23.7 | 0.5 | 6 | 1.8 | 0.04 |
| 2 | Tree cover, broadleaved deciduous | 5 465 | 1 593 | 29.1 | 11.0 | 537 | 9.8 | 3.3 |
| 8 | Tree cover, regularly flooded, salt water | 119 | 0 | 0.0 | 0.0 | 9 | 7.6 | 0.1 |
| 12 | Shrub cover, deciduous | 18 834 | 5 069 | 26.9 | 35.1 | 4 660 | 24.7 | 28.4 |
| 14 | Sparse herbaceous or sparse shrub cover | 69 608 | 1 894 | 2.7 | 13.1 | 9 412 | 13.5 | 57.4 |
| 16 | Cultivated and managed areas | 15 056 | 4 544 | 30.2 | 31.5 | 1 093 | 7.3 | 6.7 |
| 19 | Bare areas | 77 530 | 1 035 | 1.3 | 7.2 | 223 | 0.3 | 1.4 |
| 20 | Water bodies | 1283 | 150 | 11.7 | 1.0 | 250 | 19.5 | 1.5 |
| 22 | Artificial surfaces | 1 969 | 67 | 3.4 | 0.5 | 217 | 11.0 | 1.3 |
| | Total | 188 791 | 14 280 | | 100 | 16 157 | | 100 |

[1] Pixel size: 1x1km; [2] urban extents are excluded; [3] TDP - total degrading pixels; [4] TIP - total improving pixels.

Comparison of degrading areas with land use systems (Tables 5 and 6) indicates that 44 per cent of degrading land is rangeland (herbaceous vegetation in the FAO legend, 8 per cent of this unit), 30 per cent is agricultural land (28 per cent of agricultural land), 10 per cent is forestry (about one third of the forest area) and 6 per cent is bare. Of the improving land, 73 per cent of is rangeland, 8 per cent is agricultural land and 11 per cent of is classified as urban.

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

| *Code* | *Land use system* | *Total pixels (TP)* | *Degrading pixels (DP)* | *DP/TP* | *DP/TDP*[1] | *Improving pixels (IP)* | *IP/TP* | *IP/TIP*[2] |
|---|---|---|---|---|---|---|---|---|
| | | ( 5'x5' ) | ( 5'x5' ) | ( % ) | ( % ) | ( 5'x5' ) | ( % ) | ( % ) |
| 0 | Undefined | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 1 | Forestry - not managed (natural) | 3 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 2 | Forestry - protected areas | 1 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 4 | Forestry - pastoralism moderate or higher | 14 | 3 | 21.4 | 1.8 | 2 | 14.3 | 1.0 |
| 5 | Forestry - pastoralism moderate or higher with scattered plantations | 36 | 14 | 38.9 | 8.3 | 7 | 19.4 | 3.6 |
| 6 | Forestry - plantations | 2 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 7 | Herbaceous - not managed (natural) | 97 | 0 | 0.0 | 0.0 | 7 | 7.2 | 3.6 |
| 8 | Herbaceous - protected areas | 4 | 1 | 25.0 | 0.6 | 0 | 0.0 | 0.0 |
| 9 | Herbaceous - extensive pastoralism | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 10 | Herbaceous - moderately intensive pastoralism | 515 | 25 | 4.9 | 14.8 | 65 | 12.6 | 33.2 |
| 11 | Herbaceous - intensive pastoralism | 306 | 48 | 15.7 | 28.4 | 71 | 23.2 | 36.2 |
| 13 | Rain-fed agriculture | 3 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 14 | Agro-pastoralism - moderately intensive | 2 | 1 | 50.0 | 0.6 | 0 | 0.0 | 0.0 |
| 15 | Agro-pastoralism - intensive | 126 | 37 | 29.4 | 21.9 | 7 | 5.6 | 3.6 |
| 16 | Agro-pastoralism - moderately intensive or higher with large-scale irrigation | 44 | 11 | 25.0 | 6.5 | 9 | 20.5 | 4.6 |
| 17 | Agriculture – large-scale irrigation (> 25% pixel size) | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 18 | Agriculture - protected areas | 1 | 1 | 100.0 | 0.6 | 0 | 0.0 | 0.0 |
| 19 | Urban areas | 126 | 16 | 12.7 | 9.5 | 23 | 18.3 | 11.7 |
| 20 | Wetlands - not managed (natural) | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 21 | Wetlands - protected areas | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 22 | Wetlands - mangroves | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 23 | Wetlands - agro-pastoralism | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |

| *Code* | *Land use system* | *Total pixels (TP)* | *Degrading pixels (DP)* | *DP/TP* | *DP/TDP*[1] | *Improving pixels (IP)* | *IP/TP* | *IP/TIP*[2] |
|---|---|---|---|---|---|---|---|---|
| | | ( 5'x5' ) | ( 5'x5' ) | ( % ) | ( % ) | ( 5'x5' ) | ( % ) | ( % ) |
| 24 | Bare areas - not managed (natural) | 572 | 10 | 1.7 | 5.9 | 1 | 0.2 | 0.5 |
| 25 | Bare areas - protected | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 26 | Bare areas - extensive pastoralism | 50 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 27 | Bare areas – moderately intensive pastoralism | 247 | 0 | 0.0 | 0.0 | 2 | 0.8 | 1.0 |
| 28 | Water - coastal or not managed (natural) | 7 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 29 | Water - protected areas | 2 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 30 | Water - inland fisheries | 8 | 2 | 25.0 | 1.2 | 2 | 25.0 | 1.0 |
| 100 | Undefined | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| | Total | 2166 | 169 | | 100.0 | 196 | | 100.0 |

[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] |
|---|---|---|---|---|---|---|---|---|
| | | ( 5'x5' ) | ( 5'x 5' ) | (%) | (%) | ( 5'x 5' ) | (%) | (%) |
| Forestry | 1-6 | 54 | 17 | 31.5 | 10.1 | 9 | 16.7 | 4.6 |
| Rangeland | 7-11 | 922 | 74 | 8.0 | 43.8 | 143 | 15.5 | 73.0 |
| Agricultural land | 13-18 | 176 | 50 | 28.4 | 29.6 | 16 | 9.1 | 8.2 |
| Urban | 19 | 126 | 16 | 12.7 | 9.5 | 23 | 18.3 | 11.7 |
| Wetlands | 20-23 | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| Bare areas | 24-27 | 869 | 10 | 1.2 | 5.9 | 3 | 0.3 | 1.5 |
| Water | 28-30 | 17 | 2 | 11.8 | 1.2 | 2 | 11.8 | 1.0 |
| Undefined | 0,100 | 0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| Total | | 2164 | 169 | | 100.0 | 196 | | 100.0 |

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

### 3.10.2 Relationship with population density

About 15 per cent of Tunisians (1.5 million out of 9.9 million in 2005) live in the degrading areas; 11 per cent live in the improving areas (Figure 14). There is no clear statistical relationship between land degradation, or land improvement, and rural population density: there is a weak, positive correlation ($r^2$=0.05) between land degradation and $\log_e$ population density and, also, a weak, positive correlation ($r^2$=0.08) between $\log_e$ population density and land improvement (Figure 15).

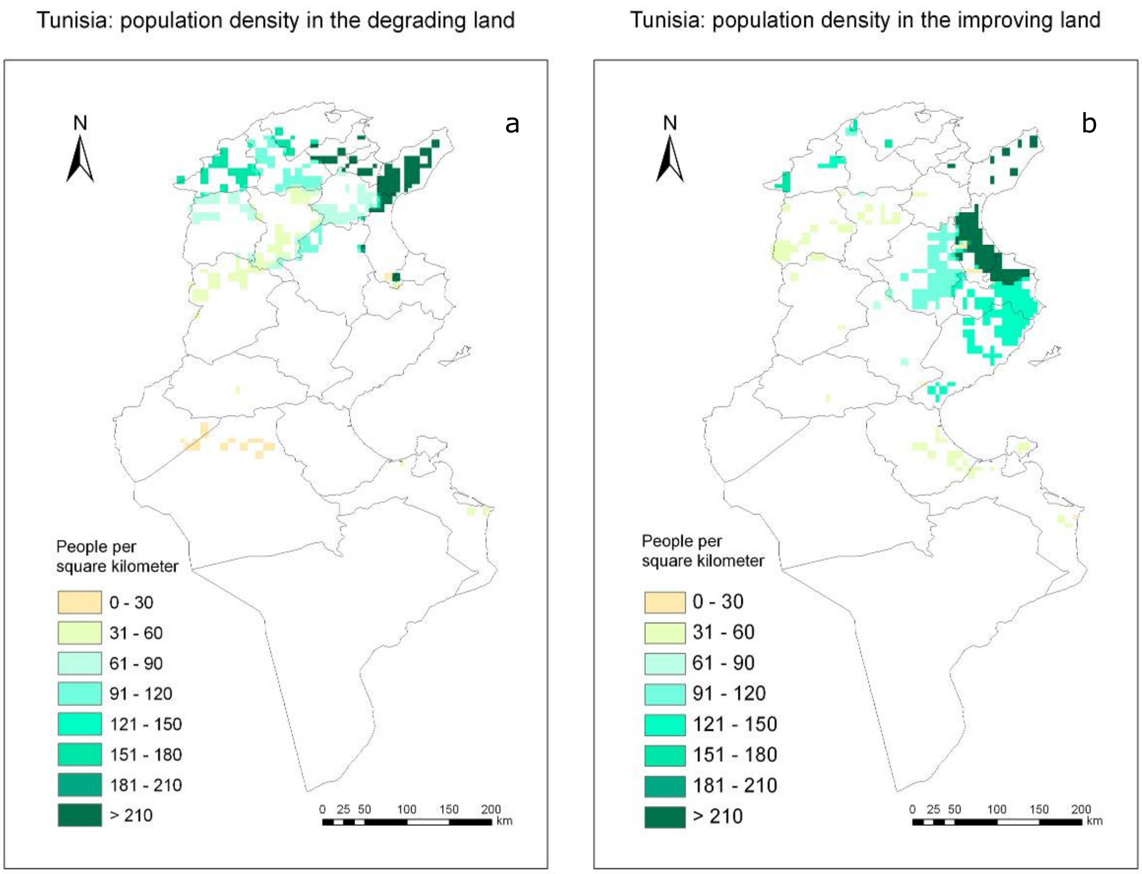


**Figure 14. Population density in the degrading areas (a) and in the improving areas (b)**

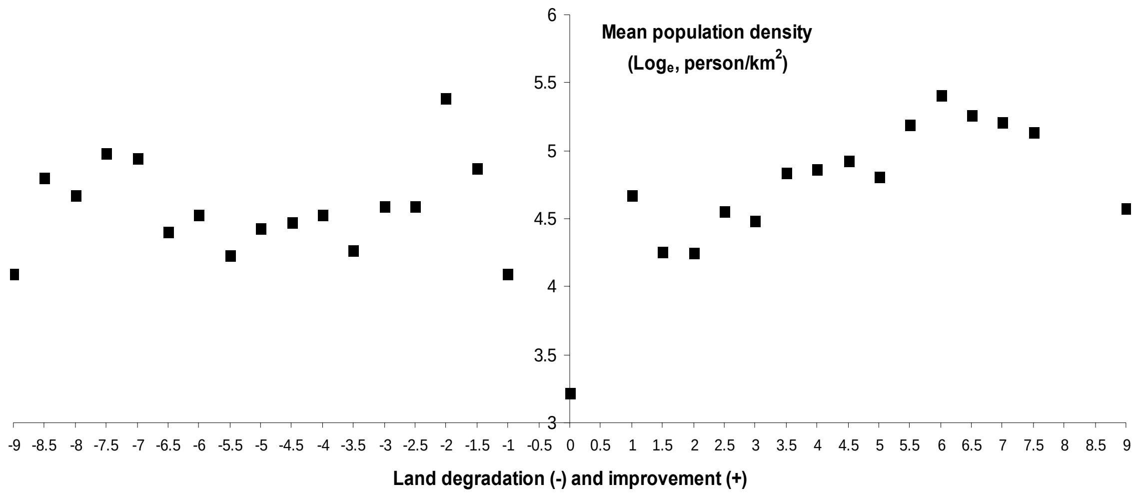


**Figure 15. Relationship between population density and land degradation and improvement**

### 3.10.3 Association with aridity

There is no obvious correlation ($r^2$=0.05) between land degradation and Turc's aridity index; 64 per cent of degrading areas is semi-arid, 24 per cent dry sub-humid, 4 per cent humid, and 8 per cent arid or hyper-arid.

### 3.10.4 Association with poverty

Taking the percentage of children under five years of age who are underweight as a proxy for poverty, there appears to be no relationship ($r^2$=0.004). More rigorous analysis is needed to tease out the underlying biophysical and social and economic variables. This could be done using more specific geo-located data e.g. from household surveys.

# 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 off GIMMS time series NDVI data, i.e. a measure of greenness, which is taken as a proxy for NPP. Translation of NDVI is robust but approximate.

- The proxy is several steps removed from recognisable symptoms of land degradation as it is commonly understood - such as soil erosion or salinity; the same goes for land improvement. Greenness is determined by several factors and, to interpret it in terms of land degradation and improvement, these other factors must be accounted for – in particular variability of rainfall and temperature 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 NDVI though with lesser amplitude. Land use change is not taken into account in this study owing to the 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 is usually associated with a loss of NPP but it may or may not be accompanied by soil erosion, compaction and salinity, and it may well be profitable and sustainable , depending on management. Similarly, increasing NPP means greater biological production but may reflect, for instance, encroachment of bush or invasive species – which is not land improvement as commonly understood.

- The coarse resolution of the GIMMS data is a limitation: an 8km pixel integrates the signal from a wider surrounding area. Many symptoms of even severe degradation, such as gullies, rarely extend over such a large area; degradation must be severe indeed to be seen against the signal of surrounding unaffected areas.

- As a quantitative estimate 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 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 degradation or as a herald of improvement. Where NPP is rising but RUE is declining, some process of degradation may be under way which will remain undetected if we consider only those areas where both indices are declining. The reverse also holds true: we might not recognise 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 degradation with what is happening now. The data from the last 25 years indicate present 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 degradation; much historical degradation maybe irreversible.

- Remote sensing provides only indicators of biomass productivity. The various kinds of land degradation and improvement are not distinguished; the patterns revealed by remote sensing should be followed up by fieldwork to establish the actual conditions on the ground and results are provisional until validated in the field. This is not straightforward: an 8km pixel cannot be checked by a windscreen survey and a 23-year trend cannot 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 GLSAA interpretations 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 and improvement that are measurable on the ground?
    3. If the answer to either of the above questions is no, what has caused the observed trend?
    4. Is the mismatch a question of timing of observations – where the situation on the ground has subsequently recovered or reverted?

# 5 CONCLUSIONS

Land degradation and improvement have been assessed by remotely sensed indicators of biomass productivity, in particular NDVI, the greenness index, which may be translated in terms of net primary productivity (NPP). The indicators show clear decreasing and increasing trends over the period 1981-2003 which may be interpreted, respectively, as land degradation or 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 or its surrogate NDVI 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. Land use change is not accounted for in this study for lack of consistent time series data.

As a quantitative measure of land degradation, loss of NPP relative to the normal 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 a declining NPP trend.

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.

- In Tunisia, over the period of 1981-2003, overall net primary productivity increased slightly. Degrading areas, suffering a decline in climate-adjusted NPP, occupy 8 per cent of the country, mostly in the well-watered north, and suffered an average loss of NPP of 14 kgC/ha/year.

- Of the degrading areas, half is scrubland (8 per cent of the total scrubland area); one third is cropland (30 per cent of the arable).

- About 15 per cent of Tunisians (1.5 million out of a total of 9.9 million) live in the degrading areas. However, correlations between rural population density and land degradation are weak and there is no correlation between land degradation and proxy indicators of poverty. More rigorous analysis is needed to tease out the underlying social and economic drivers.

- Land improvement, defined by increase in NPP, RUE and EUE, is identified across 9 per cent of the country. Of the improving area, 87 per cent is scrub and grassland, 7 per cent cropland, and 3 per cent forest.

- GLADA presents a different picture from previous assessments of land degradation which compounded historical land degradation with what is happening now. The data for the period since 1981 indicate current trends but tell us nothing about the historical legacy. Severely degraded areas are not distinguished by this analysis if there has been no further change over recent years; the same applies to long-improved areas that are now maintained in a stable condition. However, 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; the various kinds of land degradation and improvement are not distinguished. The patterns identified by remote sensing should be followed up by fieldwork to establish the actual conditions on the ground.

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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 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 negative trend in climate-adjusted NDVI were overlaid on the other maps. Corresponding comparative values were calculated, pixel-by-pixel and a univariate correlation calculated.

# Appendix 2: NDVI indicators of 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 | 0.100 | 0.201 | 0.155 | 74.3 | 25.7 | 0.829 | 0.728 | 0.447 | 0.0012 | 0.0016 | 0.0005 |
| Maximum | 0.242 | 0.467 | 0.343 | 77.2 | 22.8 | 0.655 | 0.297 | 0.437 | 0.0018 | 0.0013 | 0.0011 |
| Max-Min | 0.093 | 0.316 | 0.189 | 66.8 | 33.2 | 1.055 | 0.670 | 0.500 | 0.0015 | 0.0013 | 0.0006 |
| Mean | 0.179 | 0.286 | 0.234 | 76.4 | 23.6 | 0.688 | 0.293 | 0.447 | 0.0013 | 0.0011 | 0.0007 |
| Sum | 2.144 | 3.433 | 2.812 | 76.4 | 23.6 | 0.688 | 0.293 | 0.447 | 0.0150 | 0.0128 | 0.0082 |
| STD | 0.029 | 0.102 | 0.060 | 69.1 | 30.9 | 1.104 | 0.641 | 0.621 | 0.0005 | 0.0004 | 0.0002 |
| CoV | 0.117 | 0.385 | 0.230 | 55.6 | 44.4 | 1.001 | 0.780 | 0.182 | 0.0020 | 0.0018 | 0.0002 |

*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.

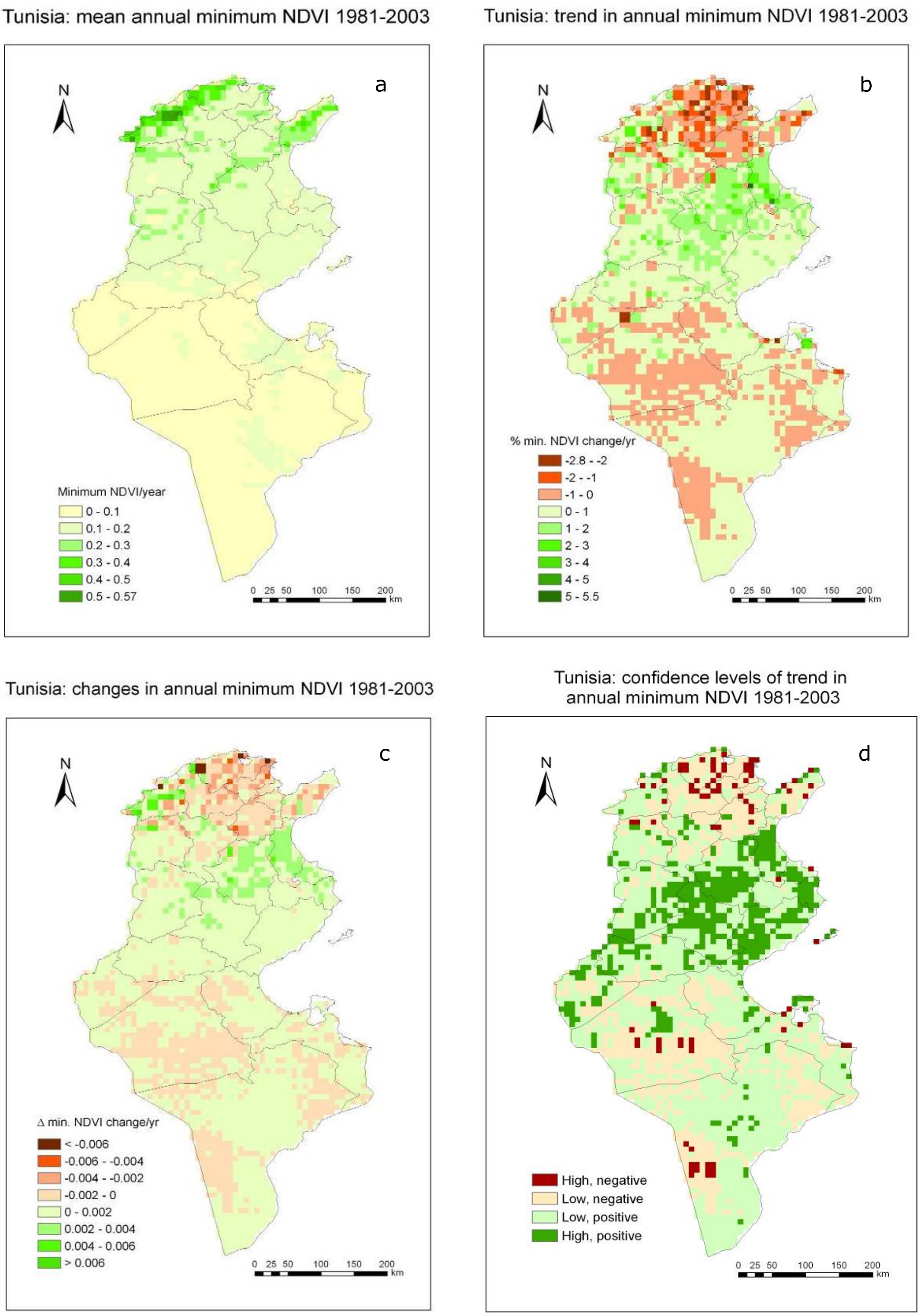


**Figure A1. Annual minimum NDVI 1981-2003: Multi-year mean (a) and trends (b – percentage, c – absolute, d - and confidence levels)**

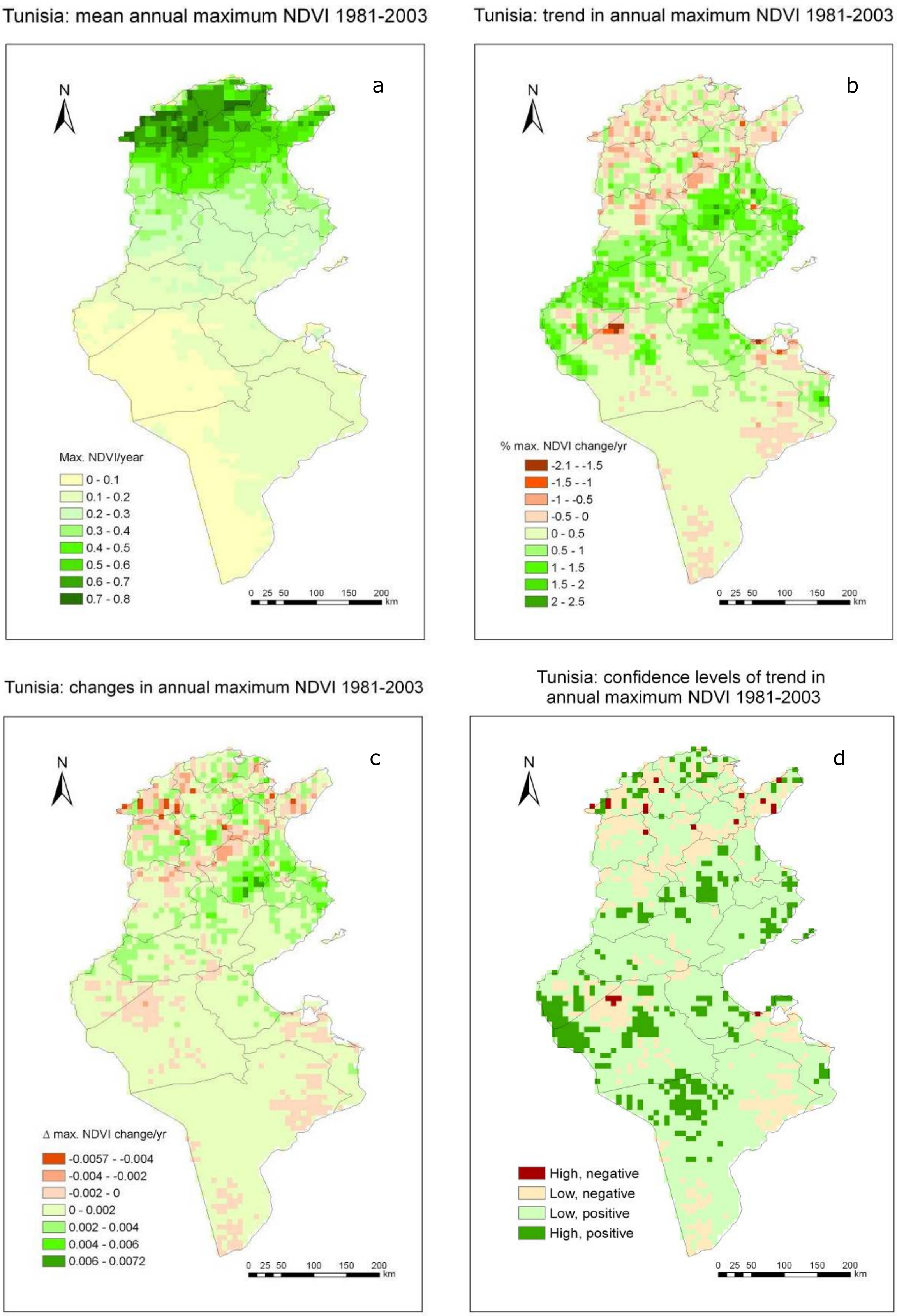


**Figure A2. Annual maximum NDVI 1981-2003: multi-year mean (a) and trends (b - percentage, c – absolute, d - confidence levels)**

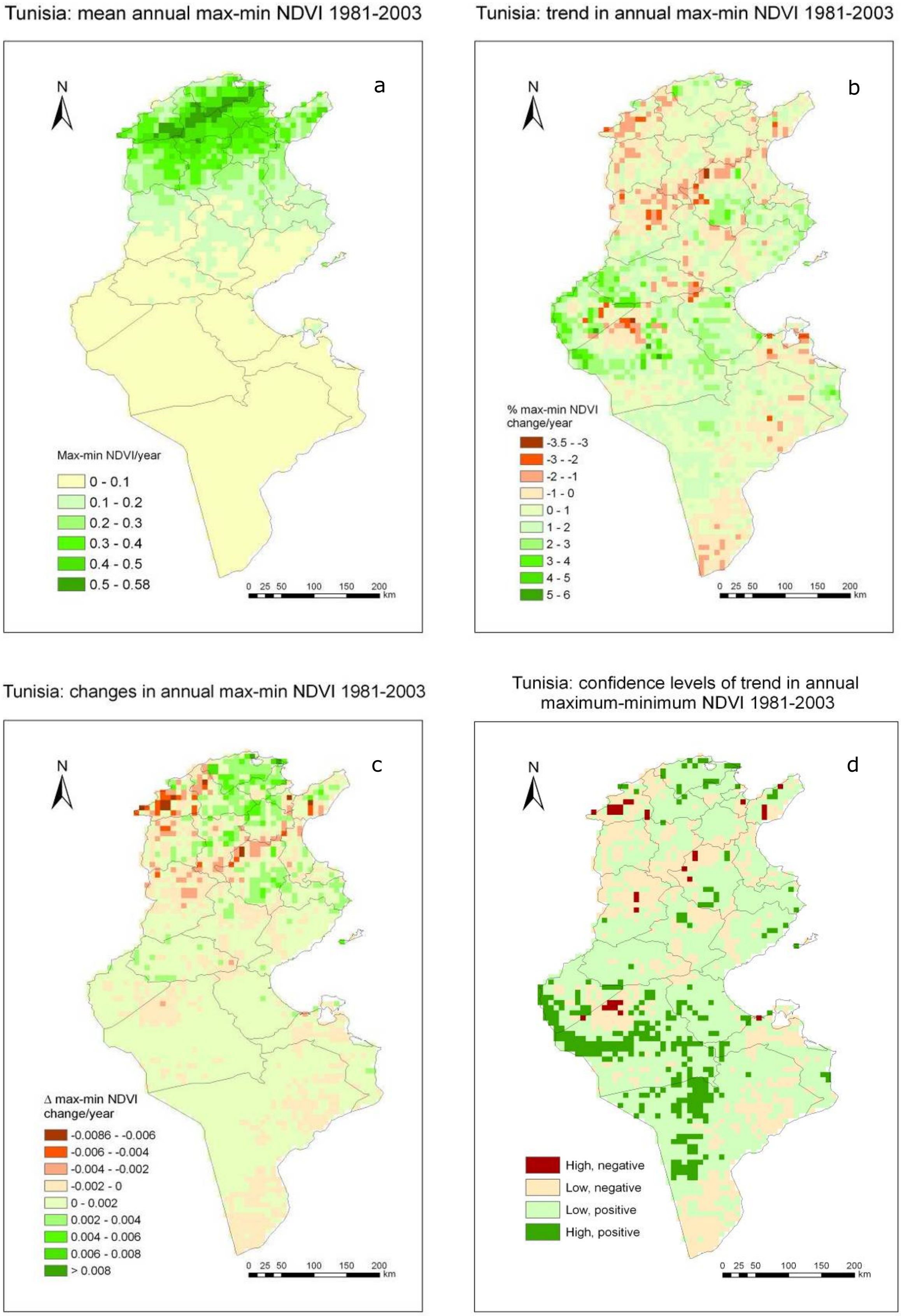


**Figure A3. Max-min NDVI 1981-2003: multi-year mean (a), trends (b - percentage, c – absolute, d - confidence levels)**

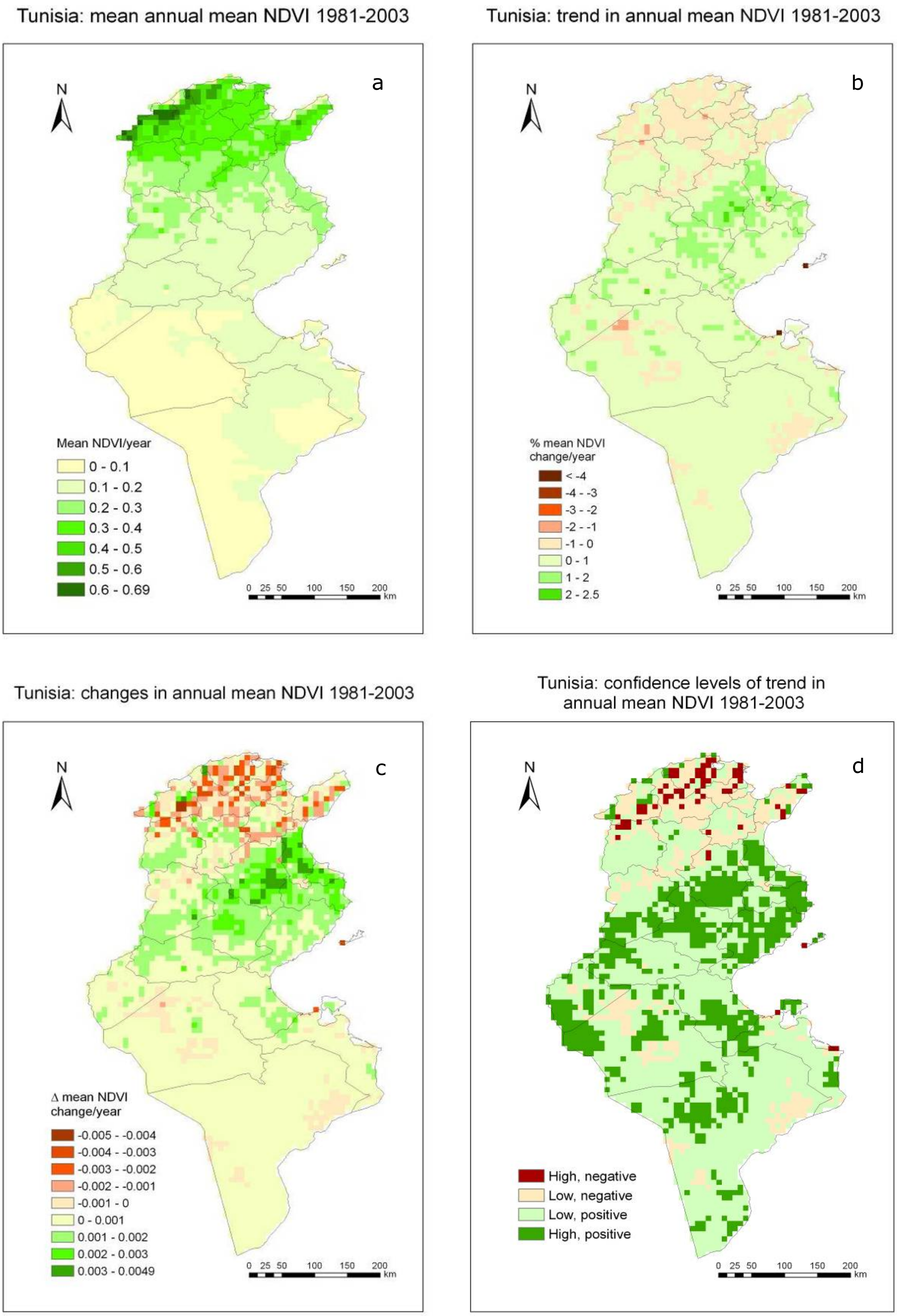


**Figure A4. Mean NDVI 1981-2003: multi-year mean (a) and trends (b - percentage, c – absolute, d - confidence levels)**

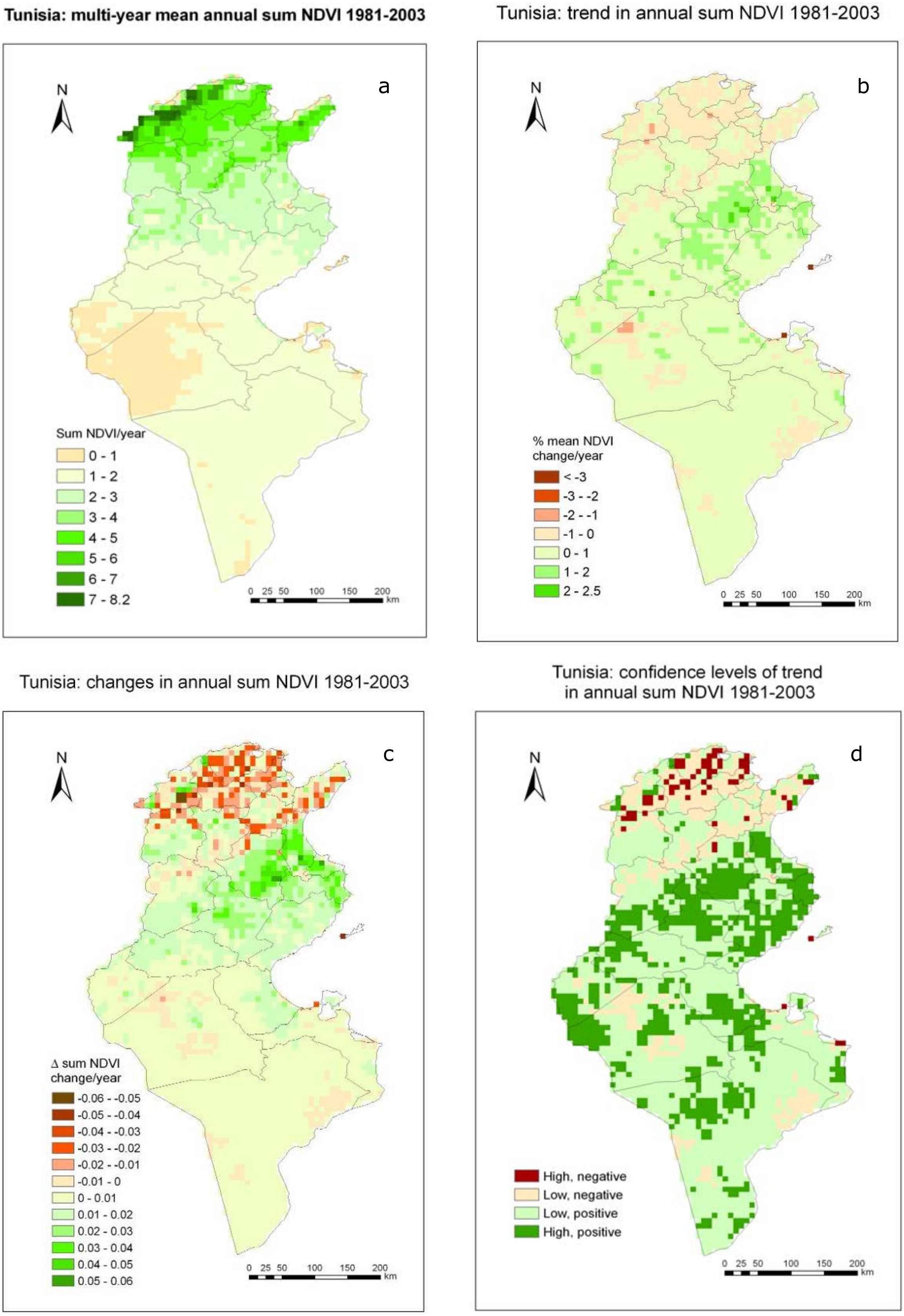


**Figure A5. Annual sum NDVI 1981-2003: multi-year mean (a) and trends (b – percentage, c – absolute, d - confidence levels)**

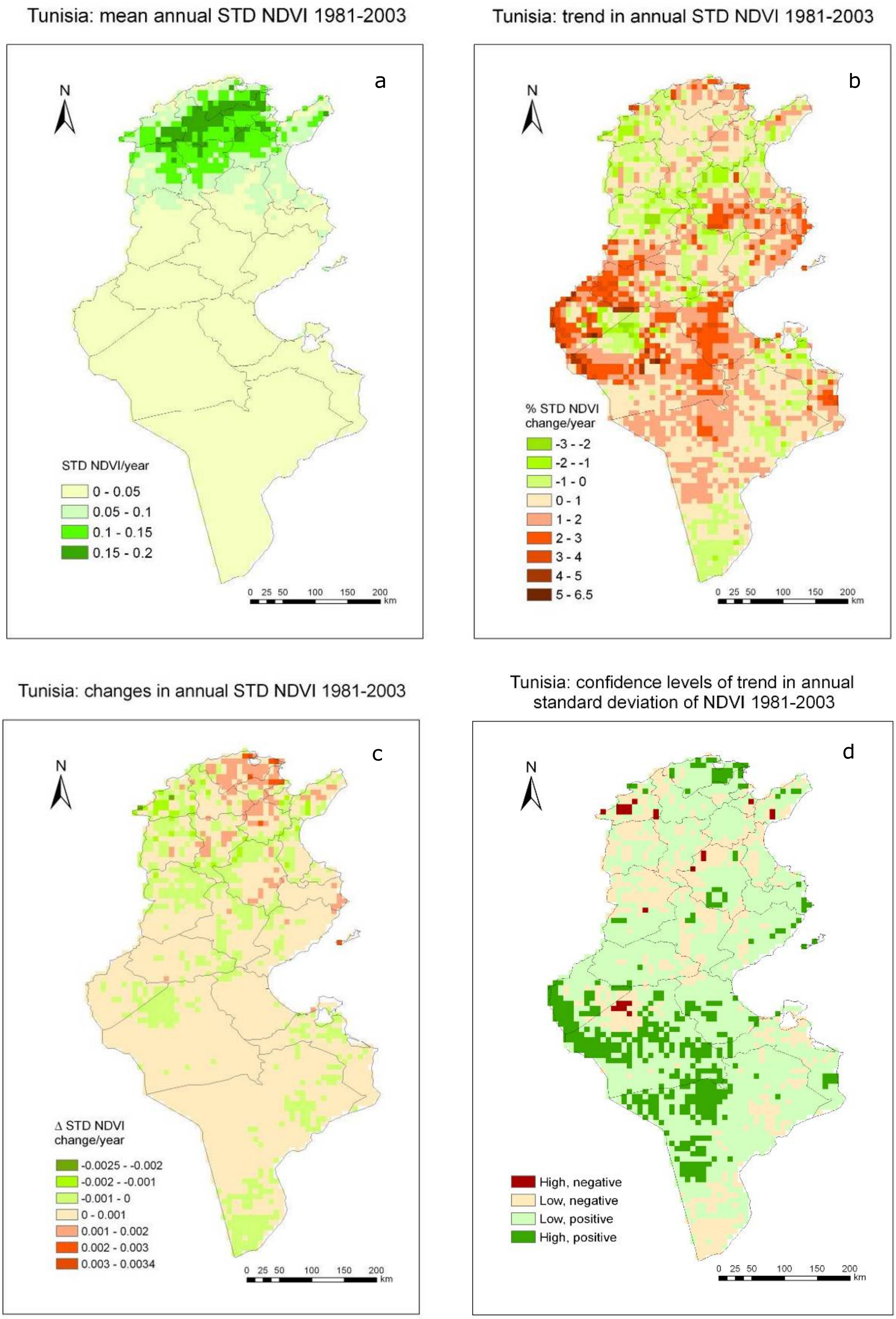


**Figure A6. NDVI standard deviation 1981-2003: mean (a) and trends (b - percentage, c – absolute, d - confidence levels)**

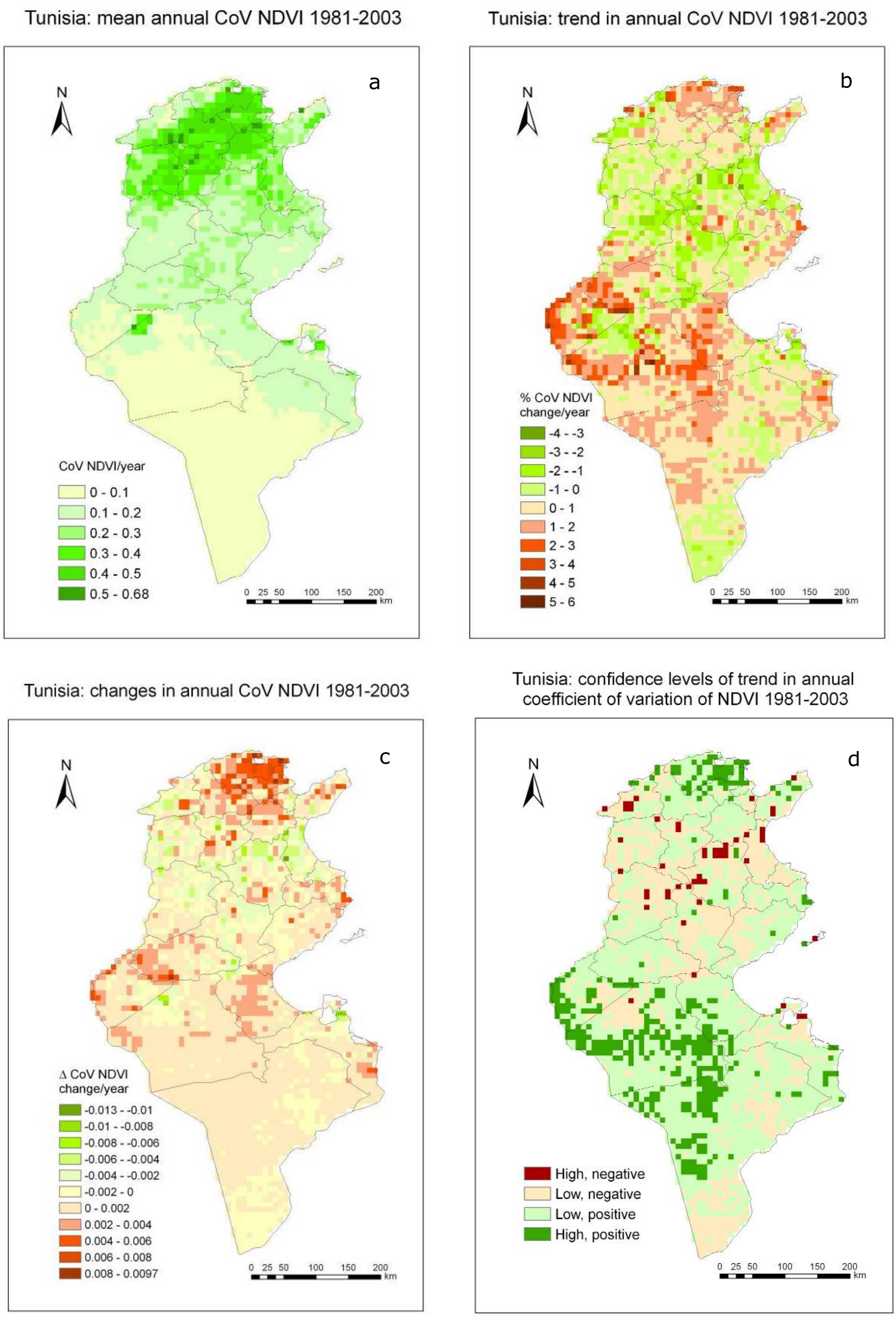


**Figure A7. NDVI coefficient of variation 1981-2003: mean (a) and trends (b - percentage, c – absolute, d - confidence levels)**