## 1 INTRODUCTION AND SCOPE

The African continent is increasingly recognized as one of the few areas in the world where development is lagging and is attracting increasing attention of the donor community. With population pressures increasing and the low investments made in land conservation, the future health of the land is in question (Vlek, 2005). This study emerged as the result of a simple question on where and how to invest research dollars on land degradation in sub-Saharan Africa in order to identify causes and remedies or coping strategies for this problem. Before deciding on how, the question on where needs to be resolved. The challenge was to find a way to point the scientific community to the regions in Africa that are under threat. The sub-continent has an extent of over 20 million square kilometres with an average population density of 30 persons per km$^2$ (over half of which live in cities). Indeed, quantifiable data on this topic are incredibly scarce and a visit to the library or a search in the internet nets very little useful information. Though a GOOGLE Search yields nearly 2 million hits, the very first of those is a rather sobering paper by Prof. S.C. Nana-Sinkam of the Joint ECA/FAO Agriculture Division (www.fao.org/docrep/X5318E/x5318e02.htm) that starts out by stating: Little reliable data is available on the extent of land degradation in Africa. However, anyone who has travelled through the continent has observed that land degradation is widespread and serious. Setting research priorities based on mere observations seemed dubious. This provided the incentive to find a way to conduct a more systematic inventory of the state of the land in sub-Saharan Africa (SSA).

Land is central to development in Africa since the livelihoods of about 60 per cent of the population are dependent on agriculture (Moyo, 2000). Africa's total land area covers 29.6 million km$^2$, of which two-thirds is arid or semi-arid (UNEP, 1992). Many papers cite various critical numbers when it comes to land degradation in Africa. For instance, Reich et al. (2001), claim that about 25 per cent of the land in Africa is prone to water erosion and about 22 per cent to wind erosion. GEF (2006) claims that 39 percent of the African continent, and as much as 65 percent of agricultural land are affected by desertification. Often these are educated guesses or statements based on expert surveys such as the Global Assessment of Soil Degradation - GLASOD (Oldeman et al., 1990). In the latter, 290 national collaborators, guided by 23 regional correlators were asked to estimate human induced decline in land productivity by degree as light, moderate, strong and extreme. The latter two categories were considered non-reclaimable at farm level. With each – relatively homogeneous - mapping unit classified as to extent (0-5, 5-10, 10-25, 25-50, 50-100%) and degree of degradation, the combination yielded a classification of severity of degradation (light, moderate, severe and very severe). The national collaborators also identified the major cause for degradation associated with the mapping unit. Twelve degradation types were mapped. In the process of reporting and using the GLASOD data, the concepts of land and soil were interchanged and confused by many of its users.

The original GLASOD data were digitized, and identified for individual countries. It is possible to take either degree or severity of degradation as a basis. Table 1 shows the degree of soil degradation as a percentage of the total land area that has its productivity reduced by the defined amount of area covered. When the survey was conducted in the late eighties, the degree of land degradation in sub-Saharan Africa suggested that 83% of the surveyed area was not degraded and 6% each was lightly or moderately degraded. The remainder was considered in worse condition and beyond reclamation, which at 5% seems modest. Yet, no other continent reaches this degree of degradation and as percentage of the present arable land area its significance jumps to 25 %, assuming that reported degradation was primarily observed on agricultural land.

**Table 1 Degree of soil degradation by sub-continental regions (% of total area)**

| | None | Light | Moderate | Strong | Extreme |
|---|---|---|---|---|---|
| Africa | 83 | 6 | 6 | 4 | 0.2 |
| Asia | 82 | 7 | 5 | 3 | <0.1 |
| Australia | 88 | 11 | 0.5 | 0.2 | <0.1 |
| Europe | 77 | 6 | 15 | 1 | 0.3 |
| North America | 93 | 1 | 5 | 1 | 0 |
| South America | 86 | 6 | 6 | 1 | 0 |
| World: | | | | | |
| Percentage | *85* | *6* | *7* | *2* | *<0.1* |
| Area (1000 km$^2$) | *110,483* | *7,490* | *9,106* | *2,956* | *92* |

Source: World Atlas of Desertification (UNEP, 1992)

If only the actual degraded area is taken into account (as in Table 1), this may lead to an underestimation of the degradation problem. By taking the extent of degradation per mapping unit into account as well some units with high coverage of moderately degraded land are classified as (very) severely degraded. On that basis, 10% of sub-Saharan Africa is estimated to be very severely degraded and an additional 15 severely degraded (Table 2). The GLASOD maps remain somewhat subjective, dated, and rather inaccurate due to its small scale. But it remains the sole source of African soil/land degradation data. The FAO regularly revisits the GLASOD data offering more detail but maintaining most of the basic shortcomings of expert survey data (http://www.fao.org/landandwater/agll/glasod/glasodmaps.jsp).

**Table 2 Land degradation severity in sub-Saharan Africa and the world (% of area by severity class)**

| Region | Land degradation severity | | | | | Total degradation: Light – Very severe | Degradation: Moderate – Very severe |
|---|---|---|---|---|---|---|---|
| | None | Light | Moderate | Severe | Very severe | | |
| Sub-Saharan Africa | 33 | 24 | 18 | 15 | 10 | 65 | 42 |
| World | 35 | 18 | 21 | 20 | 6 | 65 | 47 |

Source: World Atlas of Desertification (UNEP, 1992)

Once a map of soil degradation has been produced, it is tempting to relate the information, reliable or not, with other mapping exercises. The FAO (Terrastat CD-ROM) undertook this for population density and found for sub-Saharan Africa that land degradation at the time was more or less linearly correlated with population density (Figure 1). Whether such a correlation represents a causal relationship or not remains to be established and is a matter of heated debate in the Land Use and Land Cover change community. Given the nature of the survey data, the GLASOD data set may not be well-suited for such relational analysis.

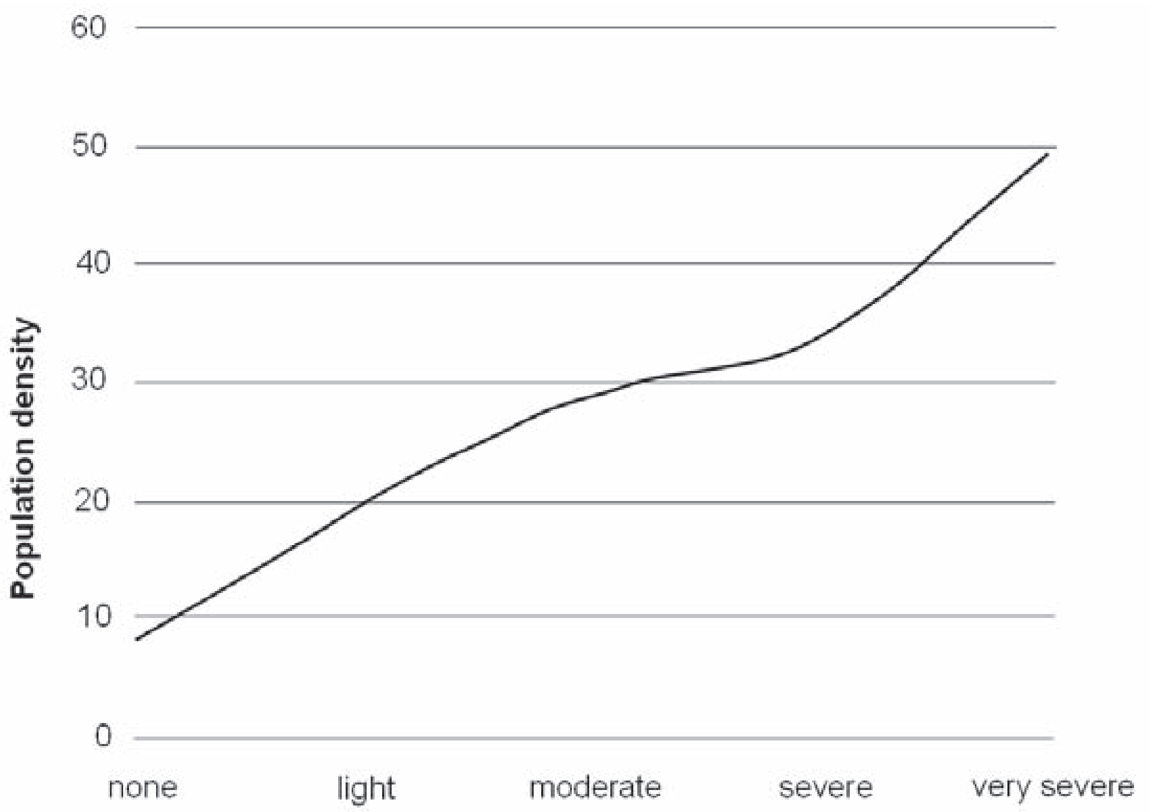



**Figure 1.Relationship between land degradation and population density in Sub-Saharan Africa. Source: extracted from FAO-Terrastat CD-ROM.**

Beyond the confusion about land and soil degradation and the subjective nature of the GLASOD study, two additional issues deserve noting. First, the expert survey is not only dated, but it provides merely a snapshot of the late 1980ies, and while it may have successfully identified the territories beyond recuperation, it fails to indicate where degradation is in progress and where it may be abating. As such it is of little help in directing research funds to gain highest returns on investment. Second, it aimed at identifying the human factor in the degradation process. However, with the little that was known at the time about the climate change impact on productivity of the land in Africa, it would have been difficult for the experts to separate these causes. Possibly these two factors are blended in the degradation type described in the GLASOD report as 'degrading agricultural practises'.

The following paper aims to address these issues. First, we review some of the criteria for distinctions between soil and land degradation. Following, we address some of the recent efforts, to capture the dynamics of land degradation, most of which by default are based on remotely sensed data. Finally, we present a relatively direct way in which we have applied such techniques and ancillary databases primarily to identify regions that deserve priority research attention.

## 2 DEFINITION AND REVIEW

Land is defined as the ensemble of the soil constituents, the biotic components in and on it, and its landscape and climatic attributes. Except for some chaotic or gradual natural events leading to land degradation, the phenomenon is mainly due to the interaction of the land with its users. According to Katyal and Vlek (2000), land degradation sets in when the potential productivity associated with a land use system becomes non-sustainable, or when the land is no longer able to perform its environmental regulatory function within an ecosystem, by accepting, storing and recycling water, energy, and nutrients. They include degradation or loss of vegetative cover, biodiversity, effective rainfall, or soil and water.

The internet yields the following definitions of land degradation:
1. A decline in the overall quality of soil, water or vegetation condition commonly caused by human activities (www.abc.net.au/learn/silentflood/glossary.htm).
2. Undesirable changes in plant &/or animal composition or abundance and undesirable changes to soil and land surface characteristics. It may be irreversible within the bounds of economic management (www.malleecma.vic.gov.au/glossarymcma.asp).
3. Reduction in capacity of the soil or vegetation to support life, through the damage to physical, chemical or biological properties, contributing to an unsustainable ecological system (www.nwpg.gov.za/soer/soernw/about_the_report/glossary.htm).
4. Land degradation is a human induced or natural process which negatively affects the capacity of land to function effectively within an ecosystem by accepting, storing and recycling water, energy, and nutrients (en.wikipedia.org/wiki/Land degradation).

By definition land degradation should thus be largely considered a social problem that, according to the USDA NRCS, is preventable through understanding and remediation of the underlying causes. The causes of land degradation are mainly anthropogenic and mainly agriculture related. They include land clearing and deforestation, agricultural mining of soil nutrients, urban expansion, land conversion, irrigation, and pollution. However, with climate being one of the attributes of land, climate change increasingly figures prominently as an underlying cause for land degradation. Land degradation affects a significant, as yet undefined portion of the Earth's arable lands, directly affecting the wealth and economic development of nations. Desertification is land degradation occurring in the most vulnerable arid, semiarid and dry sub-humid areas of the world. These susceptible dry lands cover 40 percent of the earth's surface, home to more than 1 billion people who are dependent on these lands for survival.

Soil is one of the key ingredients of land. Soil degradation, by the GLASOD definition, is a process that describes human-induced phenomena which lower the current and/or future capacity of the soil to support human life. According to the Joint Research Center of the European Commission, soil degradation is a negative process often accelerated by human activities (improper soil use and cultivation practices, building areas) that leads to deterioration of soil properties and functions or destruction of soil as a whole. The type of soil degradation refers to the degradation process (displacement of soil material by water and wind; in-situ deterioration by physical, chemical and biological processes). As a proportion of the soil-degraded area, soil erosion is the most extensive problem, estimated in the GLASOD study to be responsible for more than 80 per cent of the degraded area worldwide. Nutrient depletion causes a little over 4 per cent of the degraded area, but as it is difficult to detect may be grossly under reported (Stoorvogel and Smaling 1990). Salinity affects less than 4 per cent worldwide but 7 per cent in Asia, largely highly productive irrigated land. Problems with soil physical attributes affect 4 per cent worldwide but 16 per cent in Europe. Many of these processes are accompanied by secondary phenomena such as acidification and loss of soil organic matter.

In cultivated regions, land degradation is essentially equivalent to soil degradation. In near-natural environments such as grasslands, land degradation from over exploitation and land degradation can be reflected in loss of vegetation before this land also is affected by soil degradation (see Table 3). Within the world's dry lands, the area affected by land degradation/desertification, including soil degradation, amounts to 3600 M ha (UNEP, 1991), equivalent in size to the former USSR and China together.

**Table 3 Extent of soil degradation within the area affected by land degradation.**

| Land use category | Total area within drylands (M ha) | Area affected by land degradation (M ha) | Area affected by soil degradation (M ha) |
|---|---|---|---|
| Irrigated cropland | 145 | 43 | 43 |
| Rainfed cropland | 457 | 216 | 216 |
| Rangeland | 4556 | 3333 | 757 |
| Total | 5158 | 3592 | 1016 |

Data source: UNEP (1991)

Land use needs to be tailored carefully to its attributes in order to prevent degradation. Once degradation of land sets in, there is a high probability that societies in sub-Saharan Africa will resort to even more degrading activities in their quest to feed themselves, as farmers have few options to ameliorate their land. This interlinked process of land degradation and increased poverty, often referred to as the poverty trap (Greenland et al., 1994) eventually leads to land with such low productivity that it will not be able to restore itself. Restorative management, including proper landscape design, retention of functional biodiversity, fallowing or appropriate inputs and technology, can often halt or reverse the negative effects of exploitation by humans. When the capability or incentives (tenure) to invest in land is lacking, small and marginal farmers the world over are bound to exploit their limited resources (Syers et al., 1996). In the process, soil, the key component of land, loses quality (SSSA, 1996) and becomes infertile, saline, more erodible and compacted.

Land resources in some parts of the world are in such dire state that the hope of pulling farmers out of poverty through agricultural improvement is being put into question, calling for a new development paradigm. In the recent FAO evaluation, (FAO, 2007) it is suggested that *"In Africa, and to varying degrees in the other continents, the landholdings of the very poor are not always productive enough to lift them out of poverty and, in many such cases, under no combination of circumstances could they be made productive enough. It calls for: ....a shift in attention to rural employment for income generation and food access.... Where employment is generated in more productive areas it will also lessen the pressure on fragile areas."*

There are many indications that farmers in the fragile regions of SSA are living off public natural capital, destroying ecosystem services while barely making a living. If this new paradigm proposed by the FAO Evaluation Panel is adopted, it would be important to identify from which areas the pressure needs to be alleviated, and where the locations are of the areas that hold promise to play a significant role in overall economic development. This paradigm may be the first step from "sustainable development" to "sustainable retreat" as propagated by Lovelock (2006). The question is, how can areas be identified that are under environmental duress and degrading and which part of these call for a retreat and where is research needed to develop sustainable land use systems.

## 3 STATE OF THE ART

*What we know* has been nicely documented by Knivila in a working document on 'Land Degradation and Land Use/Cover Data Sources' (www.UNSTATS.UN.ORG/unsd/environment/_nvpdf/landdatafinal.pdf). It covers GLASOD and its regional updates ASSOD and SOVEUR as well as some other studies for regions other than SSA. It also refers to an often cited study by Dregne and Chou (1992) based on Aridity Index and data of uncertain provenance and according to Dregne and Chou, of poor quality. Further sources of information are the World Soil Resources Report 90 (FAO, 2000) as well as the Terrastat database for Africa (www.fao.org/landandwater/agll/glasodmaps.jsp) which draws from the GLASOD study. The United Nations Convention to Combat Desertification collects information from member states (www.unccd.int/cop/reports/menu.php). Some of these reports provide good information on the status of degradation, often without specifying what statistics or observations the report is based on. Finally, some individual country studies, based on expert assessment, were conducted in Africa under the auspices of the Land Use and Cover Project of the International Geosphere – Biosphere Program/International Human Dimension Program of the International Council of Science (Lepers, 2003). In short, the expert survey approach of the last century has served its purpose and without further efforts to collect better information we will continue to recast old and increasingly irrelevant information. Particularly, the information is of little help in pinpointing the areas that are in the process of degrading and need immediate (research) attention.

In recognizing this dilemma, the FAO initiated an effort to gain a better insight into land degradation under its Land Degradation Asssessment in Drylands (LADA) project with support from GEF, UNEP and UNCCD. So far the project has piloted some approaches to assess causes, status and impact of land degradation in the drylands (Van Lynden and Kuhlmann, 2002). The project aims to develop a methodological framework to assess the status, causes and risks of land degradation and will then develop a portfolio of maps for regions and countries. The effort incorporates existing maps and databases, but seeks ways of incorporating new information, particularly from the use of satellite imagery, a tool that was only a prospect at the time of the GLASOD study. The availability of long-term satellite imagery allows the tracking of changes in biomass production. In the LADA project under the Global Land Degradation Assessment (GLADA), spatial patterns and temporal trends of Nett Primary Production (NPP) – approximated by the NDVI (Normalized Difference Vegetation Index) - , and rain-use efficiency-RUE (NPP per unit of rainfall) are analysed, their trends determined by linear regression and mapped to depict spatial changes. Some of the first country studies have been recently published, notably one for Kenya (Bai and Dent, 2006) and South Africa (Bai and Dent, 2007) but the approach of arbitrarily combining two indices remains controversial.

Rich databases have been established over the years by the FAO on agricultural land (FAOSTAT), forests and inland waters (FORIS), extracted from country reports based on questionnaires. For Africa, FAO is extending this dataset using satellite imagery in the Africover project, the FAO/UNEP Land Cover Classification system (www.Africover.org). The same classification was used in Global Land Cover 2000 (GLC2000), used for the Millennium Ecosystem Assessment, which was produced by the European Commission's Joint Research Center (http://www-gvm.jrc.it/glc2000) with the help of 30 plus research teams with each team mapping its own defined region. The pre-validated dataset on the internet has a resolution of 1 km. In contrast, the Global Land Cover Characterization (GLCC) database is based entirely on Advanced Very High Resolution Radiometer (AVHRR) imagery of the early nineties with 1 km resolution, enhanced with digital elevation models and soil and land cover maps. The data is available in analyzed form from the World Resources Institute web-site (http://earthtrends.wri.org). NASA's Goddard Institute provides a 1x1 degree resolution Global Distribution of datasets for Cultivation Intensity, Vegetation, and Wetland Ecosystems (http://www.giss.nasa.gov/data/ ). The Global Land Cover Facility (GLCF) offers datasets on a wider spectrum of AVHRR resolutions (1 km, 8 km and 1 degree) from a period of 1981 – 2003. Other GLCF products are derived from MODIS (Moderate Resolution Imaging Spectroradiometer) such the Global Land Cover Facility's (GLFC) – Vegetation Continuous Fields (VCF) and Vegetation Cover Conversion (VCC) (http://glcf.umiacs.umd.edu/data/). The University of Boston/NASA Land Cover Science Data (MOD 12Q1) uses the IGBP land classification system is offered through the University of Boston web site (http://duckwater.bu.edu/lc/).

Thus, a wide variety of remote sensing (RS) products have now reached the market some with open access. The question remains to what extent they can help guide the research community toward areas where land degradation is occurring and where remedial measures need developing and implementing, or where land is relatively stable and where improvements are discernable? These are the so called hot spots, dull spots and bright spots of land degradation (Bai and Dent, 2006). Identifying these areas requires a set of indicators that can be derived from remote sensing (RS) data with a long enough track record to capture the dynamic aspects of this process. It is imperative that sufficient time series information is available with enough coverage to make statistical analysis worthwhile. The current RS databases covering Africa are sufficiently long-term and with frequent enough data sampling to meet such requirements. The numbers of indicators that can be derived from RS information are, however limited. According to the definitions listed above, land degradation should be reflected in the productivity of the land and thus in its vegetation. The most common RS derived indicator associated with vegetation productivity is the Normalized Difference Vegetation Index (NDVI). Probably best described as a relative measure of vegetation vigour and photosynthetic activity, the NDVI has been correlated with such physical measurements as total standing biomass, green leaf-area index (LAI) and per cent vegetation cover. It is most often used among other applications as a tool for monitoring temporal changes in vegetation. Thus, the two basic requirements for land degradation analysis using long term NDVI information are available. The question is whether this information can be used intelligently to suit our purpose and identify areas of human induced land degradation.

To this end we drew on the NDVI product for a 22 year period spanning from 1982 to 2003 from the Global Inventory Modeling and Mapping Studies (GIMMS), published by the Global Land Cover Facility (GLCF) (http://glcf.umiacs.umd.edu/data/gimms/). The data set is derived from imagery obtained from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA satellite series 7, 9, 11, 14, and 16. This is an NDVI dataset that has been corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change (Tucker et al., 2005). In this study, the original data was collected twice monthly between 1982 and 2003 and was aggregated to a monthly time-scale at the same resolution. To obtain the time-series of annual mean values, annual NDVI values were computed as 12-month averages. Average NDVI values for the whole period (1982–2003) of each month were also calculated. These two sets of data were then subjected to statistical analyses to assess variability and trends in vegetation productivity.

## 4 VEGETATION DYNAMICS IN SUB-SAHARAN AFRICA

### 4.1 A framework for mapping and meta-interpretation of land degradation in SSA

A logical framework to analyse the dynamics of the aboveground green biomass in sub-Saharan Africa (SSA) will have to be step-wise and include tests for significance every step of the way. The process includes two main phases: (1) the mapping of land decline in vegetation cover as a proxy for land degradation, and (2) the interpretation of the mapped degradation. Land degradation expresses itself as reduced biological productivity (Reynolds and Smith, 2002) or above ground net primary production (NPP). NDVI is strongly correlated with NPP and is often used as NPP predictor at large spatial scales (Field et al., 1995; Prince and Goward, 1995). Thus, this study principally utilized monthly composite NDVI data (1982-2003) to assess the spatial and temporal patterns of land degradation. In order to account for differences in biomes, the sub-Saharan region was subdivided according to annual rainfall, representing dry (<800 mm yr$^{1}$), sub-humid (800- 1500 mm yr$^{1}$) and humid zones (>1500 mm yr$^{1}$).

Above-ground net primary production (represented by NDVI) has been shown to increase with increasing annual precipitation (Huxman et al., 2004), and indeed correlation studies between rainfall and NDVI have been used to differentiate between human induced and climate induced land degradation (Herrmann et al., 2005) where any NDVI trends not explained by rainfall dynamics are ascribed to human actions. In this study, monthly rainfall totals for the period 1981-2002 were used to determine the green biomass response to rainfall variability in the study region. Pixels with NDVI changes in accordance with rainfall may see vegetation decline due to climate change. Pixels not affected by rainfall are those where green biomass change could be interpreted to reflect areas with strictly human induced land degradation. For those regions, the variability and trends over time of green biomass (approximated by annual NDVI) were analyzed. Following statistical analysis, the areas where vegetation decline was significant in absolute or relative terms were studied in greater detail. Land-cover and land quality maps of Africa were used to relate the observed land degradation to the various land attributes, its uses and natural vegetation covers. To analyze the potential impact of population on land degradation, mean pixelized population density data extracted for SSA were used. The major analyses conducted in this study are described below.

The sequential analysis in this study resulted in a classification scheme presented in Table 4. Each pixel was characterized with respect to its mean annual precipitation, long-term response to annual rainfall, and trend in green biomass over time (1982-2003) offering 27 degradation classes. Since this study focused on areas with decreasing green biomass, the classes representing pixels lacking or with a positive green biomass trend over time were omitted from Table 4.

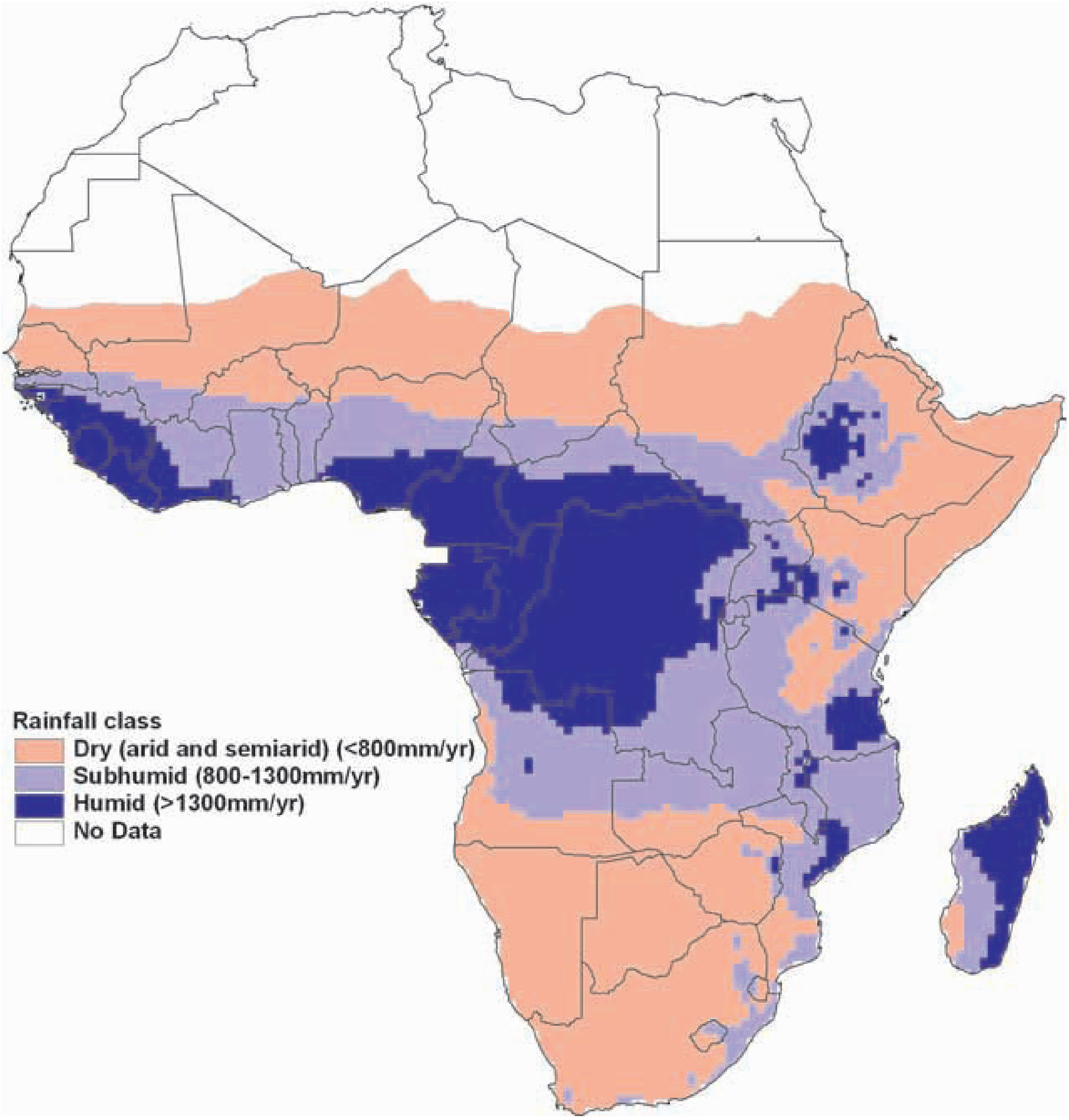
**Table 4 Scheme of sequential classifiers for each pixel analyzed in mapping of land degradation in SSA.**

| Classifier 1: Mean annual precipitation (MAP) | Classifier 2: Long-term biomass response to rainfall (parameter: Pearson's correlation coefficient) | Classifier 3: Long-term declining trend of green biomass (Parameter: Slope of inter-annual NDVI) | Degradation class |
|---|---|---|---|
| Dry (arid and semi-arid) | Negative | Decrease | Dry-Negative-Decrease |
| | Neutral | Decrease | Dry-Neutral-Decrease |
| | Positive | Decrease | Dry-Positive-Decrease |
| Subhumid | Negative | Decrease | Subhumid-Negative-Decrease |
| | Neutral | Decrease | Subhumid-Neutral-Decrease |
| | Positive | Decrease | Subhumid-Positive-Decrease |
| Humid | Negative | Decrease | Humid-Negative-Decrease |
| | Neutral | Decrease | Humid-Neutral-Decrease |
| | Positive | Decrease | Humid-Positive-Decrease |

### 4.2 Precipitation zones

The sensitivity to human interference or rainfall fluctuations of aboveground NPP is substantially different across biomes (Knapp and Smith, 2001; Huxman et al., 2004). The major biomes are defined by annual rainfall. In the approach selected for this study we therefore first divided SSA into three rainfall zones based on the mean annual precipitation (MAP). Annual rainfall data for the period of 1982 – 2002 were extracted from the dataset of Climatic Research Unit (CRU) at the University of East Anglia (UK), which consists of land-only grid monthly rainfall data at a spatial resolution of 0.5° covering the period from 1901 – 2002 (Mitchell and Jones, 2005). After cross referencing with the independent VASClimo dataset (Beck et al., 2005), pixels of these grids were resized to match the resolution of AVHRR - NDVI data (8 km), yielding 21680441km$^2$ / 64km$^2$ = 338757 pixels. The delineated climate zones in Sub-Saharan Africa (SSA) were as follows:

- Arid and semi-arid (*Dry*) MAP < 800 mm/yr
- Tropical sub-humid (*Subhumid*): 800 mm/yr ≤ MAP≤ 1300 mm/yr
- Tropical humid (*Humid*): MAP > 1300 mm/yr




**Map 1 Main precipitation zones delineated using mean annual precipitation (MAP) during the past 22 years (1981-2002).**

The boundaries were selected somewhat arbitrarily but such that they agree with main agroclimatic zones for Africa. Map 1 shows the mean precipitation zones extracted for the SSA region. Compared to the most recent Köppen-Geiger climate map (Kottek et al., 2006), the Dry zone in this figure more or less matches the arid and semi-arid climates (*BW* and *BS* classes), the *Subhumid* zone overlays the tropical dry-wet (savanna) climate (*Aw* class), and the *Humid* zone matches the humid equatorial climate (*Af* and *Am* classes). Dependent on the aim of these types of analysis, other classifications can be easily introduced.

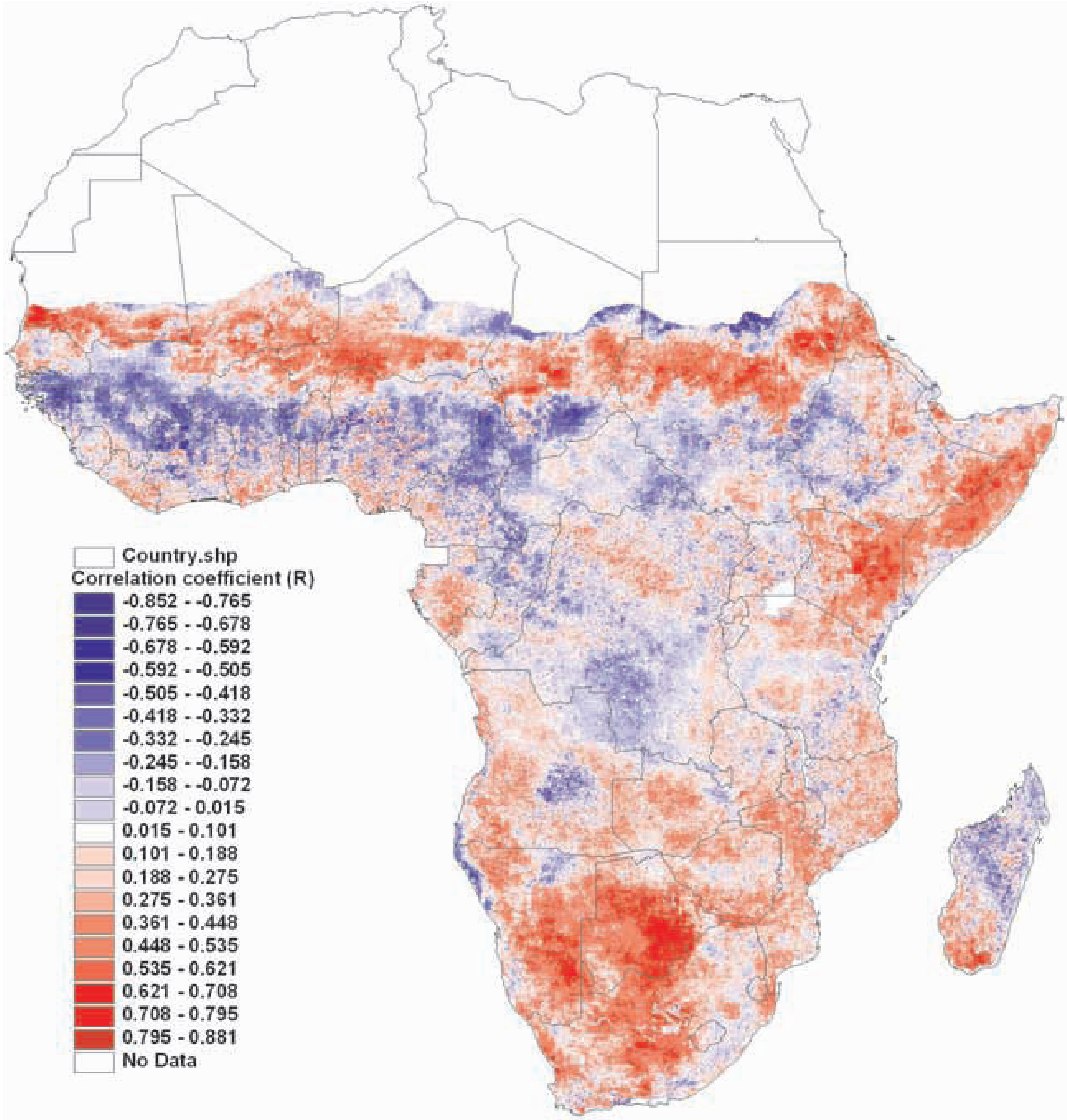
### 4.3 Biomass (NDVI) response to inter-annual rainfall

Various studies report that the spatial and temporal differences in the NDVI are closely related to climate in many environments (Eastman and Fulk, 1993; Ichii et al., 2002). In fact, temporal variations in the NDVI may be representative of the vegetation's response to climate variability (Nicholson et al., 1990; Potter and Brooks, 1998). Thus, the NDVI has been widely used to monitor ecosystem dynamics and to detect the spatial extent and temporal variability of land degradation (Tucker and Choudhury, 1987; Groten and Ocatre, 2002).

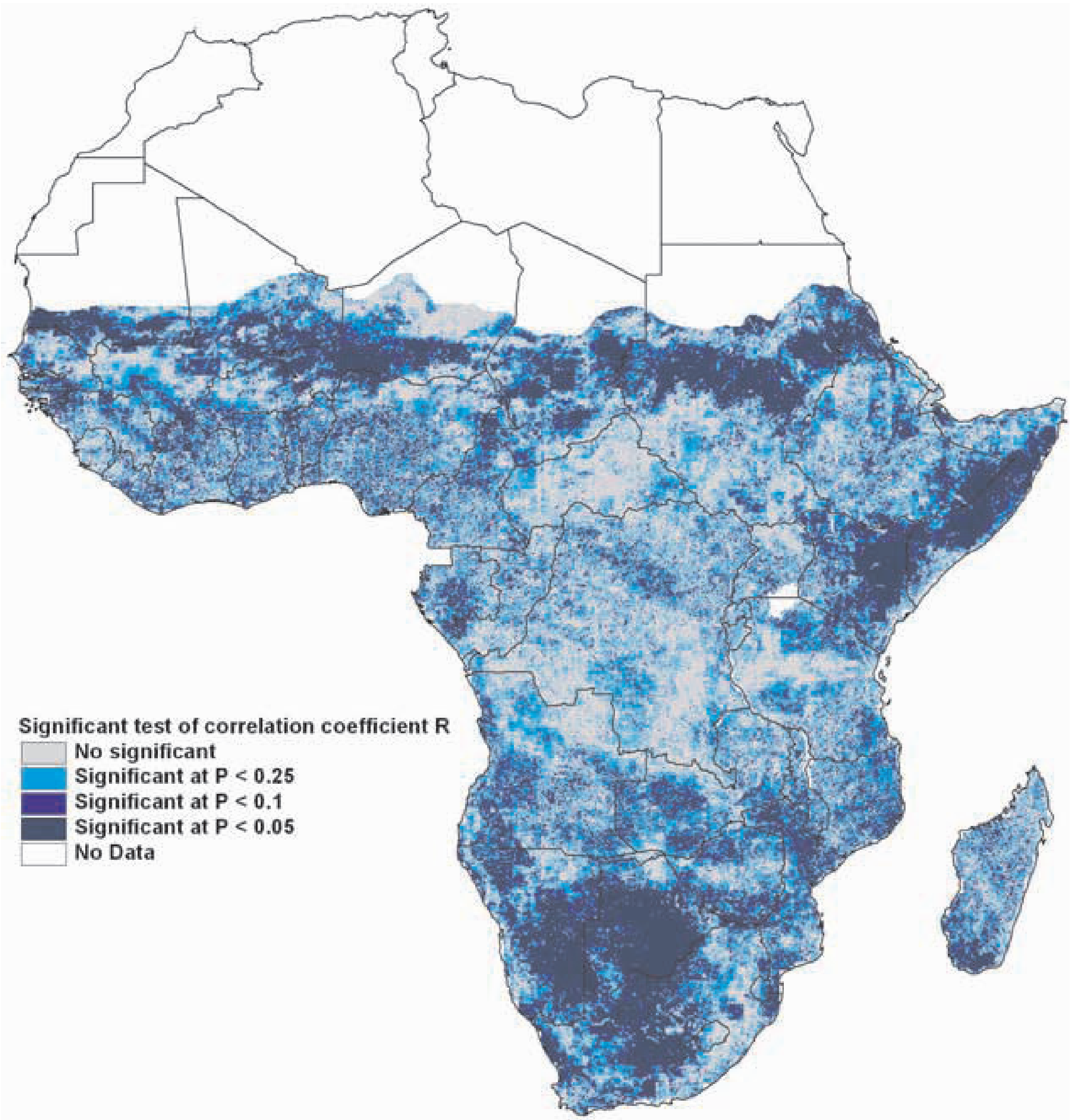
In order to eliminate from this study on human induced land degradation those regions where climate has had a dominant impact on vegetation, the correlation between green biomass (NDVI) and rainfall across SSA over the 20-years period was assessed. The relationship between inter-annual green biomass and rainfall dynamics was measured using Pearson's correlation coefficient for the period 1982-2002 for each pixel (Map 2a). Correlations varied from +0.88 to -0.85, with the red colours in Map 2a indicating the extensive zones where vegetation correlates positively with rainfall changes from year to year, a zone covering the Sahelian band and the semi-desert regions of southern Africa. The blue zones indicate areas where the opposite has occurred: when rainfall goes up the vegetation cover goes down nonetheless (possibly severe degradation), or rainfall goes down but vegetation goes up (possibly human intervention through irrigation or aforestation). The blue area stretches along the sub-humid band from Southern Chad to the Casamance of Senegal. The non-responsive areas are found in the high rainfall zones where the variation of rainfall is limited, or in the very dry zones where the variation is too high to yield significance.

The correlation coefficient of every pixel was tested for statistical significances at different confidence levels: 95% ($P < 0.05$), 90% ($P < 0.1$), and 75% ($P < 0.25$) (Map 2b). Details of the pixel-based correlation analysis and significance tests are explained in Supplementary Information 1. A pixel was considered to have a strong correlation between its inter-annual NDVI and rainfall if the correlation coefficient is significant ($P < 0.05$) and greater than 0.45 or lower than -0.45. An overlay of Map 2a and 2b yielded Map 2c with those areas where pixels show a correlation coefficient of at least $|0.45|$ and statistical significance at $P < 0.05$. Those pixels that showed a significant (>95%) positive correlation (in yellow) were considered areas where precipitation shifts over the past 20 years had affected biomass signals (NDVI), possibly masking human effects on vegetation.

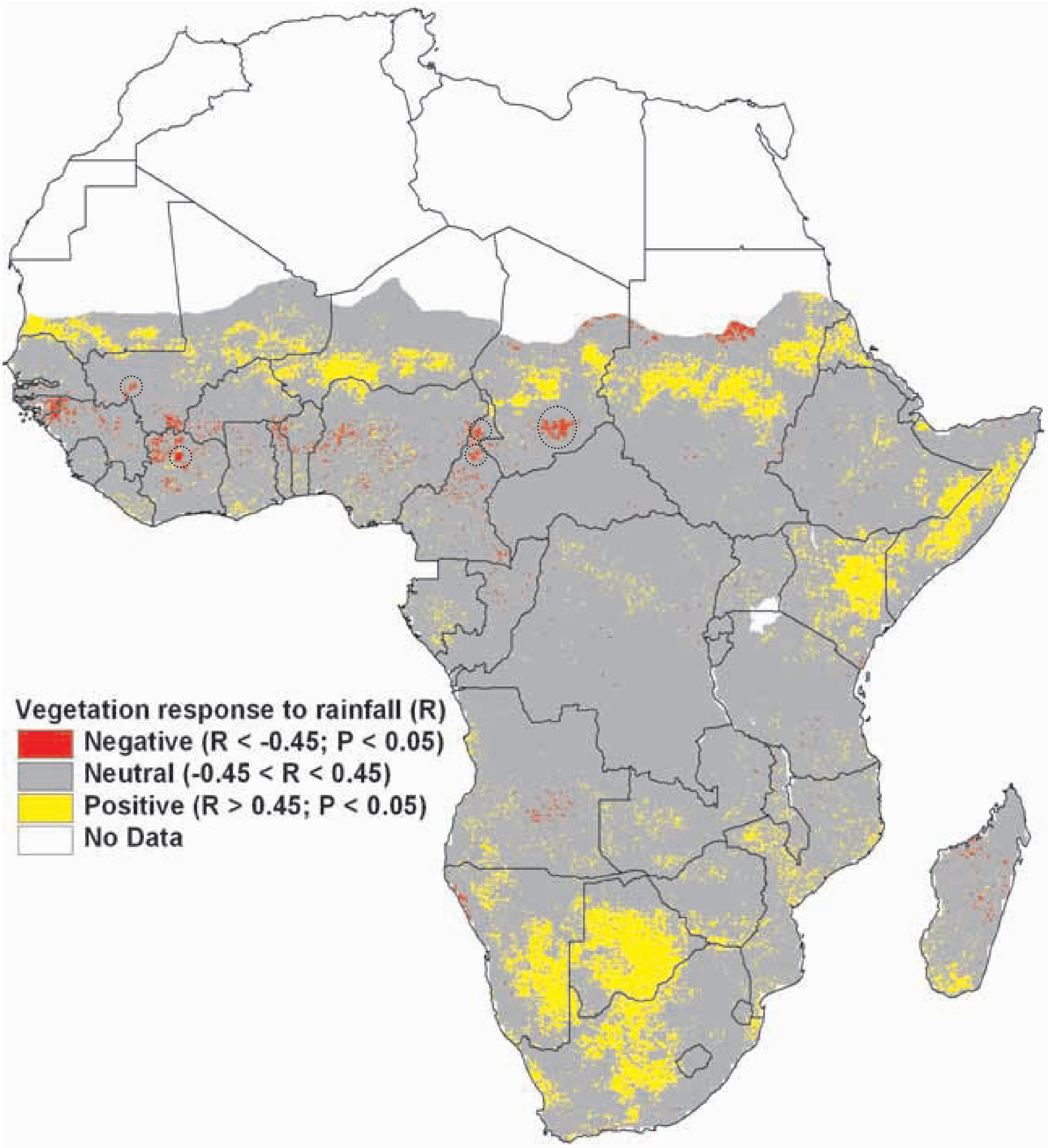
Beside the yellow area in Map 2c where vegetation significantly and positively correlated with rainfall, without offering information on the direction of the actual NDVI shifts. Areas with a significant negative correlation are shown in red. These areas may represent significantly declining vegetation despite improving rainfall conditions, possibly due to soil degradation, such as the red spots with circles in Map 2c, thus areas of particular concern. Alternatively, they may represent areas where NDVI is improving despite a decline in rainfall. This would most likely be due to human interference such as the establishment of exclusion zones, reforestation schemes or new irrigation schemes. A comparison with the FAO- Global Map of Irrigation Areas (Siebert et al., 2005; Siebert et al., 2002) confirmed this for Central Sudan.




**Map 2a Pearson's coefficient of correlation between annual NDVI and rainfall over the period 1982-2002.**



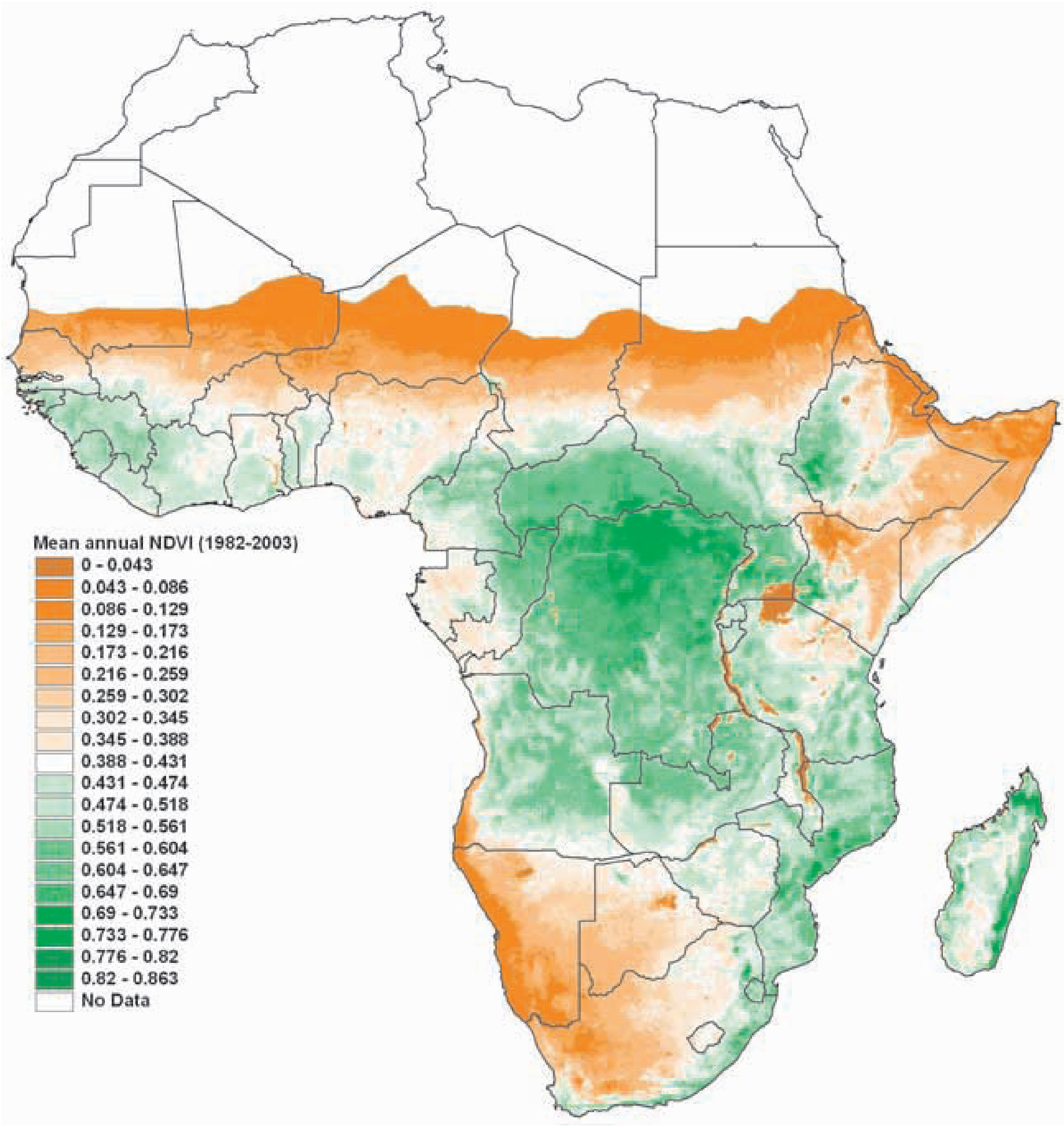

**Map 2b Map of pixel-based significant test for Pearson's coefficient between annual NDVI and rainfall ($R_{xy}$) during the period 1982-2002.**




**Map 2c Zones of long-term vegetation response to changing mean annual precipitation delineated by Pearson's correlation coefficient (its magnitude and statistic test) for the period 1982 – 2002.**

### 4.4. Long-term trend in biomass dynamics

The next step was to assess the NDVI dynamics *per sé* over time, using time series of nearly the same period (1982 – 2003) on a pixel-by-pixel basis. Map 3 shows the mean annual NDVI for the period of interest, ranging from 0 to 0.86. Not surprisingly, there is reasonably good correspondence between vegetation and rainfall zones (Map 1) but with exceptions, notably the coastal areas of Nigeria, Cameroon and Gabon, with rainfall suitable for dense vegetation. The relatively low NDVI for this high-rainfall zone seen in Map 3 possibly reflects early (before 1980) deforestation of this highly populated area.




**Map 3 Mean annual NDVI during the period 1982 – 2003.**

The NDVI time series was then statistically analysed based on linear regression to identify those areas that showed a significant decline or increase in NDVI over time. The temporal trend of vegetation greenness (NDVI) is measured by the slope coefficient (A) in the simple linear relationship: NDVI = A×Year + B and B is an indicator for a possible delay in the onset of degradation. For every pixel, the slope A was computed (Map 4a) and tested for statistical significance at different confidence levels: 95% ($P < 0.05$), 90% ($P < 0.1$), and 75% ($P < 0.25$) (Map 4b). Details of the pixel-based linear trend analysis and significance tests are explained in Supplementary Information 2. This exercise yields the area where, at least from a birdseye view, a significant and worrying loss of vegetation cover was taking place (in blue) and those where NDVI is increasing (in red). The range in the rate of decline or improvement is similar (the slope A ranges from -0.013 to 0.016).

The statistical test results (Map 4b) show that the geographic extent of significant degradation in vegetation cover is sensitive to a shift in confidence level. Given the very dynamic nature of human induced degradation it seems reasonable to accept the somewhat relaxed confidence level of 90%. Even then, it is clear from a visual comparison of Map 4a and 4b that some of the highest significance levels are found for areas where change in NDVI has been minor. These areas lie in the Sahelian and Horn of Africa regions as well as in dry parts of southern Africa where NDVIs are very small to begin with (Map 3). Small changes in absolute NDVI values may still constitute large changes in relative terms in these biomes.

To take a closer look at these regions, it appears useful to express change in NDVI as a percentage of what it was at the beginning of the observation period resulting in Map 4c. The use of 1982 as a baseline seems appropriate as it appears to properly represent the rainfall of the early eighties in the Sahel (Anyamba and Tucker, 2005). This map confirms the area of significant change in NDVI in absolute terms, but clearly shows that other areas are significantly changing in relative terms. The extent and overlap is summarized in Table 5. For the purpose of this study, absolute and relative changes in NDVI are treated as being of equal significance. Table 5 reveals that the area of overall NDVI decline is only a fraction (one-fifth) of the area improving in NDVI. Before offering an analysis of the decline in NDVI, an explanation for the widespread improvement is called for.

**Table 5 Areas that experienced a significant change in NDVI in absolute or relative terms or both, between 1982 and 2003 (Note: total SSA study area covers 22 million km$^2$).**

| Declining biomass trend | Area (km$^2$) | % | Improving biomass trend | Area (km$^2$) | % |
|---|---|---|---|---|---|
| Declining absolute NDVI only | 435,261 | 20 | Improving absolute NDVI only | 787,395 | 8 |
| Declining relative NDVI only | 407,806 | 19 | Improving relative NDVI only | 2,057,859 | 20 |
| Declining both absolute and relative NDVI | 1,339,652 | 61 | Improving both absolute and relative NDVI | 7,584,837 | 73 |
| *Total area of declining biomass* | *2,182,719* | *100* | *Total area of improving biomass* | *10,430,091* | *100* |

In order to obtain a better insight on where these changes in NDVI are taking place, the sub-Saharan region was subdivided in arid, semi-arid, sub-humid and humid zones and the extent of areas with declining, improving or neutral NDVI attributed to each zone (Table 6). A large proportion of the improving areas are found in the arid zone such as the Sahelian and Horn of Africa regions as well as parts of Botswana as demarcated in Map 4c. This phenomenon has been recently reported in the literature as the "greening of the Sahel" (Olsson, 1993; Prince et al., 1998; Tucker and Nicholson, 1999; Eklundh and Olsson, 2003; Olsson et al., 2005). These areas largely coincide with areas that are responsive to inter-annual variation (yellow areas in Map 2c). Thus, this greening might be due to a gradual improvement in annual precipitation. The early eighties were indeed characterized by a long-term draught. However, since these areas also lay below the 500 mm isohyets, averaged for the 20 years period, they are, as such, of limited agricultural consequence. The greening of the Sahel should improve the situation of the pastoralists that occupy these lands and are a vulnerable group.

**Table 6 Area ($km^2$) of different biomass trends in different climate zones**

| Zone of biomass trend* | Area ($km^2$) | | | |
|---|---|---|---|---|
| | Arid (< 500mm/yr) | Semi-arid (500 – 800mm/yr) | Sub-humid (800 – 1300 mm/yr) | Humid (> 1300mm/yr) |
| Declining areas | 299,328 | 288,384 | 903,616 | 683,968 |
| Neutral areas | 2,230,400 | 1,502,080 | 2,796,480 | 2,214,592 |
| Improving areas | 4,210,112 | 1,801,792 | 2,492,736 | 1,910,208 |
| *Total area* | *6,739,840* | *3,592,256* | *6,192,832* | *4,808,768* |

* Areas of biomass trends were delineated using linear slopes of annual NDVI (either absolute or relative) with significant tests.

The improvement in NDVI in the wetter areas can not be easily explained by rainfall trends as no such correlation could be established (Map 2c). Though the GIMMS dataset in these regions may be unreliable due to frequent cloud covers, if the phenomenon is real, one possible explanation lays in the carbon-dioxide fertilizer effect (Billings et al., 2003; Temperton et al., 2003; Tissue et al., 1997; Norby, 1987), a reaction in photosynthetic activity of the vegetation to increasing $CO^2$-levels in the atmosphere. Such an effect could be easiest observed in relatively undisturbed biomes. Indeed, 47 % of the 10.43 million $km^2$ area with improving NDVI over the SSA has a land cover of native vegetation and has very low population densities (< 8 pers/$km^2$), suggesting that NDVI improvements might indeed relate to a shift in ambient $CO^2$ levels. It would be difficult to prove this process in situ without some rather complex experimentation, but such $CO^2$ studies have been conducted elsewhere (Billings et al., 2003; Temperton et al., 2003) and the effect has been demonstrated. An alternative explanation may be the increasing NOx load of the atmosphere over sub-Saharan Africa causing an increase in reactive N deposition (Dentener, 2006). If these processes are indeed in play, it might be in play everywhere in Africa. Areas identified in Table 6 as having experienced no significant change in NDVI or a decline in NDVI would have been in worse condition without the $CO^2$- or NOx- fertilizer effect. Keeping this in mind, the remainder of this study ignores this effect and analyses the declining NDVI areas shown in Table 6.