CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH

Land decline in Land-Rich Africa

A creeping disaster in the making

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Executive Summary

The objective of this study was to identify areas of land degradation in sub-Saharan Africa as observed from space by tracking the greenness of the vegetation signal expressed as Normalize Differenced Vegetation Index (NDVI). A series of additional databases was used, and, through a step-wise amalgamation of these, conclusions were drawn about the type of (agro) ecosystems under threat. The datasets (based on 8x8 km^2 pixels) of weather and NDVI (as a proxy for net primary productivity of the land) were averaged annually from monthly observations over the last two decades of the 20th century. This is likely to have captured reduced agricultural productivity as well as loss in native vegetation cover. The logical framework to analyse and interpret the dynamics of the vegetation cover in sub-Saharan Africa (SSA) presented here allows for easy re-assessment as better of more data become available.

First, sub-Saharan Africa was divided in three zones, dry (mean annual precipitation, MAP < 800 $mm.yr^{-1}$), sub-humid (800 $mm.yr^{-1}$ < MAP < 1300 $mm.yr^{-1}$) and humid areas (MAP > 1300 $mm.yr^{-1}$), yielding three zones of similar geographic extent. In a second step we identified the regions where the annual vegetation correlates positively and significantly to changes in mean annual rainfall conditions. For those with positive correlation, vegetation dynamics are affected by climate change (or cycles) and these are not suitable to identify human induced degradation. This excluded less than 2% from further analysis.

Subsequently we looked at the slope and the significance of the vegetation index (NDVI) over time. Areas not showing a decline or increase in the NDVI, either in absolute or in relative terms, were considered stable vegetation covers. Nearly 50% of the vegetation cover in sub-Saharan Africa is experiencing a greening trend. A large fraction of this area is found in the pastoral zone below the 500 mm isohyets which has recently been reported as the "greening of the Sahel" over the period evaluated. By and in large part, this greening is due to improved rainfall in the Sahel as reflected in the positively correlation between NDVI fluctuations and rainfall. Those areas were excluded from further analysis of human induced land degradation. The remaining area with increasing NDVI might have been subject to $C0_2$ or NOx fertilization. The areas that show a consistent and significant decline in NDVI (or land degradation) over time amount to around 2.13 million km^2 or 10% of the SSA land mass. The characteristics of this area were analyzed in more detail.

Over 60 million people live on land that is losing its ability to produce green biomass due to human actions. For each rainfall zone, the mean population densities in areas with declining vegetation were more or less the same as for the rainfall zone as a whole. However, within the degrading areas, the large majority of the affected areas are thinly populated, irrespective of the rainfall zone. This would suggest that these are marginal areas with limited carrying capacities to start with. As population pressure increases, more fragile areas will be taken into cultivation causing degradation with below average population densities. These regions are likely to get worse and eventually may be best taken out of cultivation or abandoned. However, this study also identifies some degrading areas with high population densities. Often these are regions with high agricultural potential and in urgent need of remediation.

FAO data was used to delineate areas with topographical and soil constraints. Of the 2.13 million km^2 with declining vegetation, around 10,5 thousand km^2 is topographically unsuitable for agriculture but nearly 0.67 million km^2 are on soils that are considered unsuitable. Most likely farmers are occupying such marginal land due to land scarcity, but society should have an interest to avoid this. Nearly half of the remaining degrading land is on soils that are of rather poor quality. These soils may not easily be ameliorated and might never gain the resilience that good farm land requires.

Differentiation of the degradation areas according to land use type was done using the land use/land cover map of GLC2000. Of the 0.67 million km^2 that are not suitable for agriculture, 105 thousand km^2 are actually being farmed and probably should not be. Means should be found to offer alternatives to these farmers so that land can be restored over time. Of the 1.46 million km^2 that are degrading but suitable for cultivation, 0.3 million km^2 are actually farmed (agriculture and forest/cropland) and are likely over-exploited or poorly managed. Moreover, half of the suitable agricultural areas are on poor soils. These are areas where considerable research efforts should be made to identify the immediate and proximate causes of declining ground cover and develop more sustainable farming practises. A quarter million km^2 is under grassland, largely in the dry areas and most likely being over-grazed. Nearly 1.09 million km^2 are under woodland/shrubland, and forest/savanna, which each might be losing native trees as land use intensifies. Finally, 0.25 million km^2 is dense forest which is most likely being deforested.

The fraction of the land showing significant decline in vegetation cover is relatively modest (around 10%). This would correspond with the fraction of SSA with 'very severe' land degradation symptoms in the GLASOD assessment of late eighties. However, it is unlikely that any direct comparison between these two studies can in fact be made. It is more likely that these areas are additive, as the very severely degraded land from the GLASOD study would not likely show great further vegetation decline. The creeping additional loss of 10% over the last 20 years of the past century, if the pace is not stopped, translates into serious trouble for SSA in the course of the current century. In the absence of any instruments for monitoring the rate of land degradation on the ground in SSA, satellite-based systems offer the best hope for tracking the state of this vital natural resource on this vast continent. A systematic research effort should be made to verify the validity of the findings reported here and to refine the analytical tool and interpretation of the results. As more and better data-bases are placed in the public domain the current study should be updated periodically. As it stands today, the study can be used to offer guidance to the research community as well as to the donor community and policy makers:

- The current mapping exercise should be used to identify application domains, areas with common climatic, vegetation, physiographic and soil and land use characteristics that appear to be threatened by human induced land degradation. Based on this stratification, research organizations should be able to select pilot research sites where in-depth research can be undertaken to assess the total cost of land degradation (including the valuation of loss of ecosystem services) and design sustainable land management options that will maximize social benefits from the use of the land.
- Research should be undertaken to study the institutional arrangements around land access and tenure within the application domains in order to find means that will allow sustainable land management systems to be established equitably. In some cases this will be possible only through payment for ecosystem services (PES) for which the level and

beneficiaries need to be determined. The use of such instruments should be an integral part of the strategy to preserve the land for future generations.

However, some of the regions identified in this study deserve immediate attention from the donor community and policy makers:

- Identify those agricultural regions where soil and terrain conditions seem so unfavourable that immediate action is required to restore the land to its natural condition. Donor agencies could offer incentives that lead to vacating such lands by offering alternative pathways out of poverty.
- Identify areas in the humid tropics where population pressures are low but NDVI change is high as such areas are likely being deforested. Where this is taking place on poor or unsuitable soil or terrain, these practices lead to denudation and should be stopped as the land is of little agricultural use and restoration of such land is a very slow process.
- Identify areas of favourable soil and terrain where population pressure is high and degradation is in full progress. These likely are relatively resilient regions that have served as breadbaskets of Africa and require immediate attention from the development community. These are areas where fertilizer markets and land conservation measures could function and where they are likely to be profitable.

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.

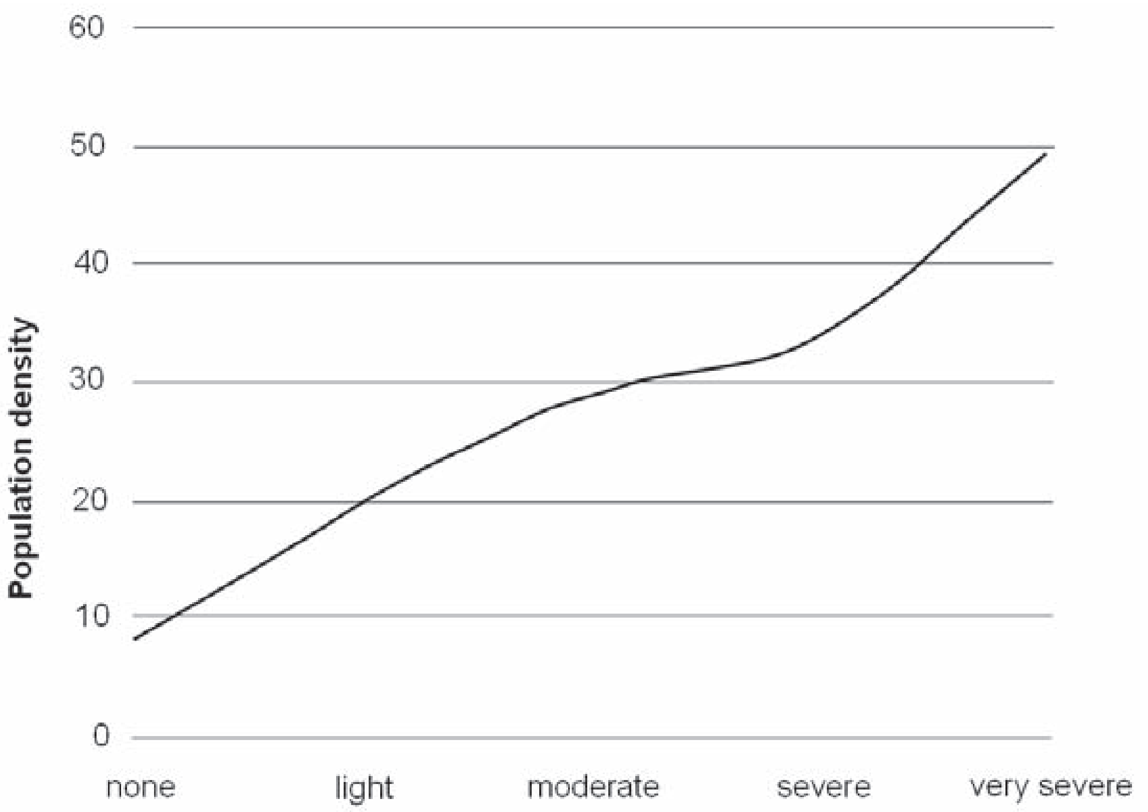


Figure 1.Relationship between land degradation and population density in Sub-Saharan Africa. Source: extracted from FAO-Terrastat CD-ROM.

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.

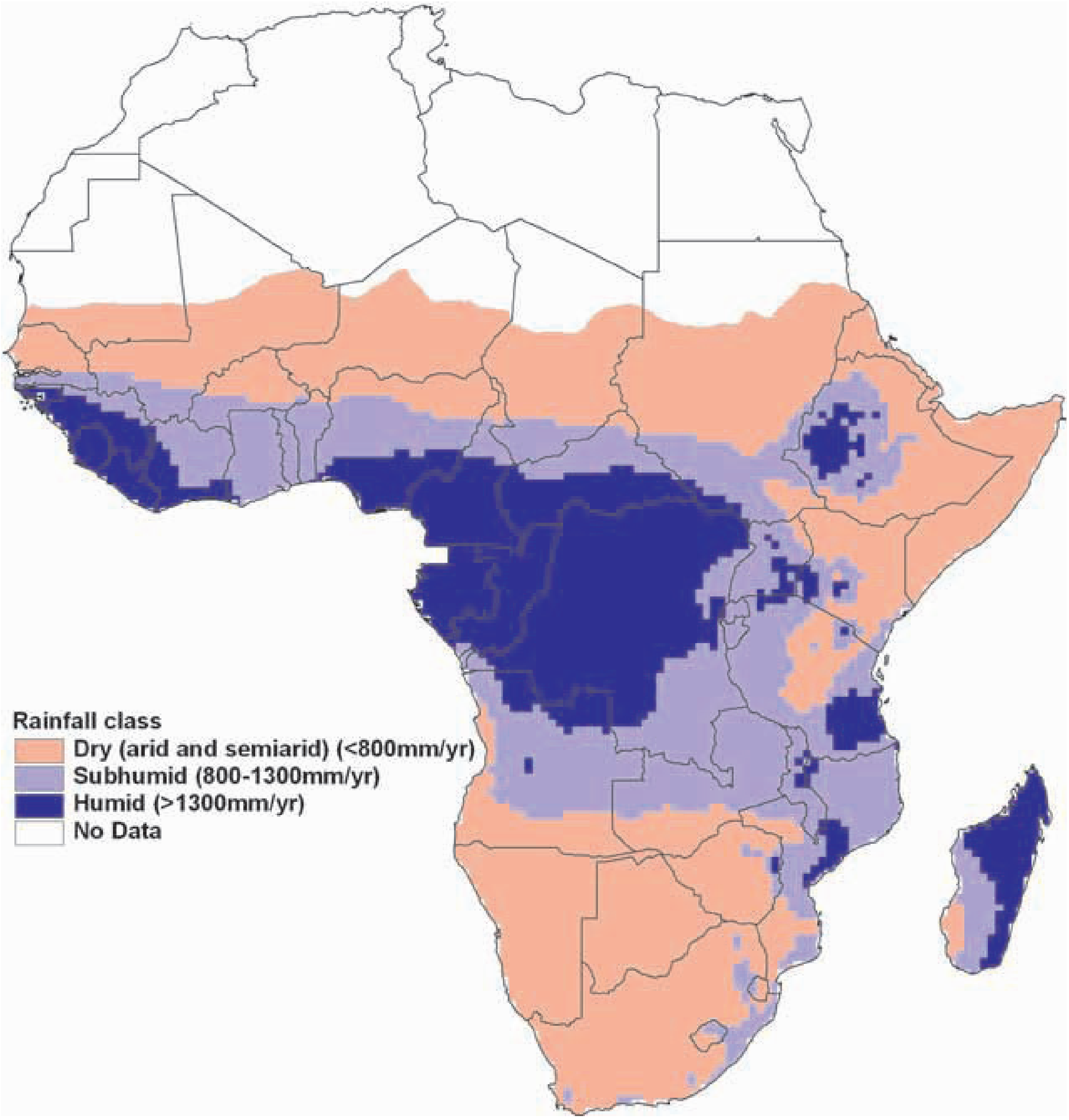
Table 4 Scheme of sequential classifiers for each pixel analyzed in mapping of land degradation in SSA.

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.

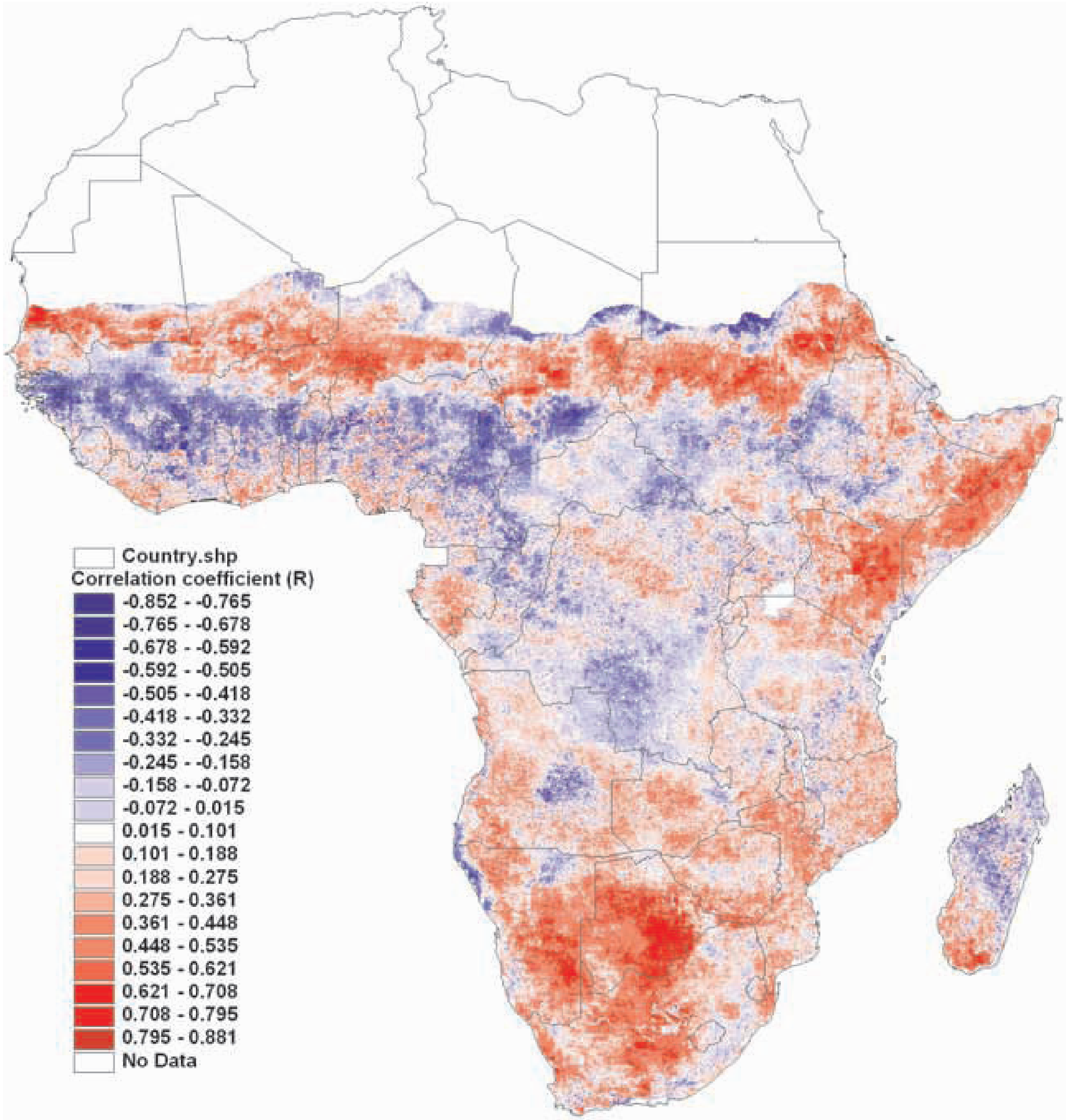
4.3 Biomass (NDVI) response to inter-annual rainfall

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).

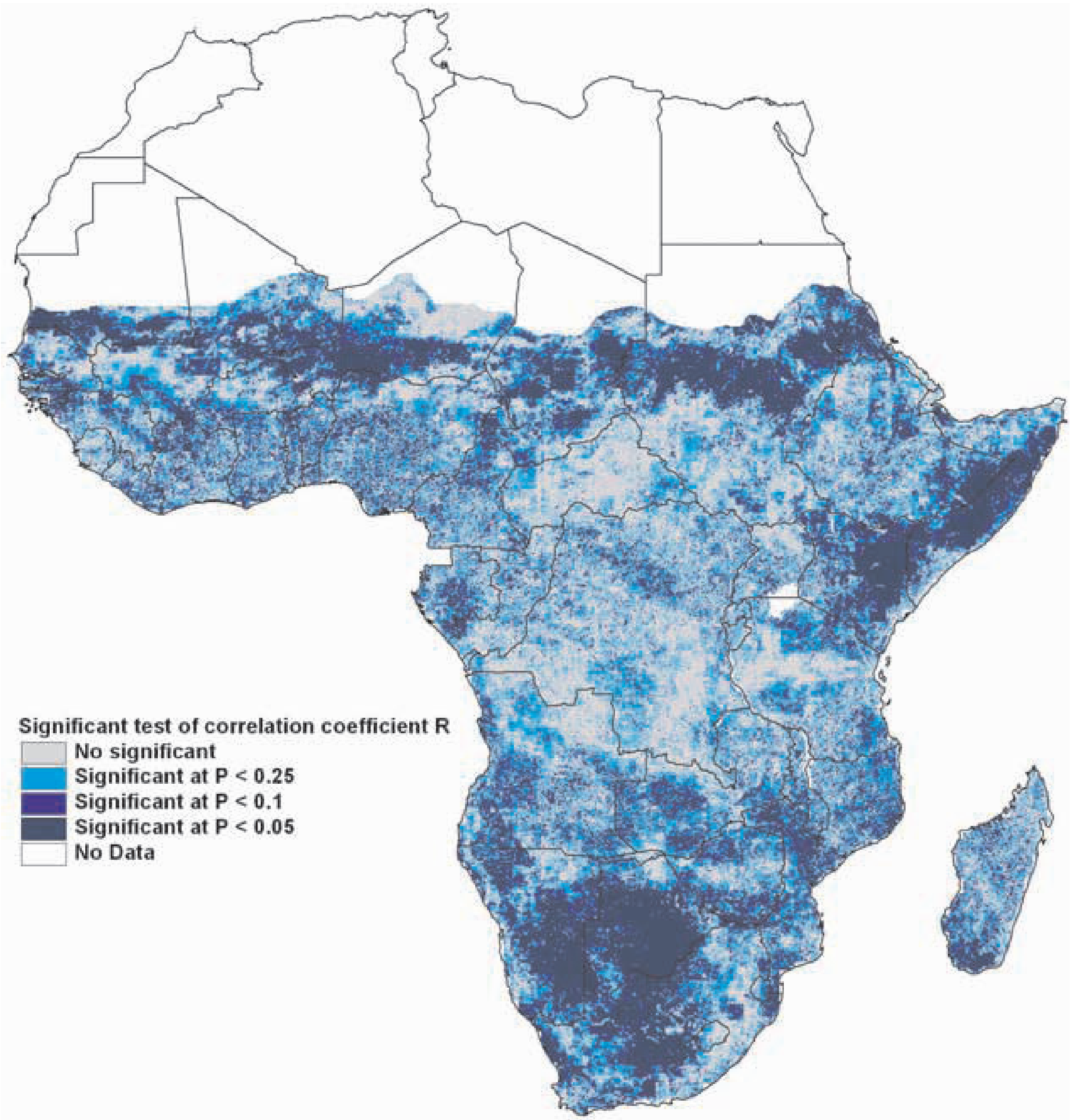
In order to eliminate from this study on human induced land degradation those regions where climate has had a dominant impact on vegetation, the correlation between green biomass (NDVI) and rainfall across SSA over the 20-years period was assessed. The relationship between inter-annual green biomass 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.

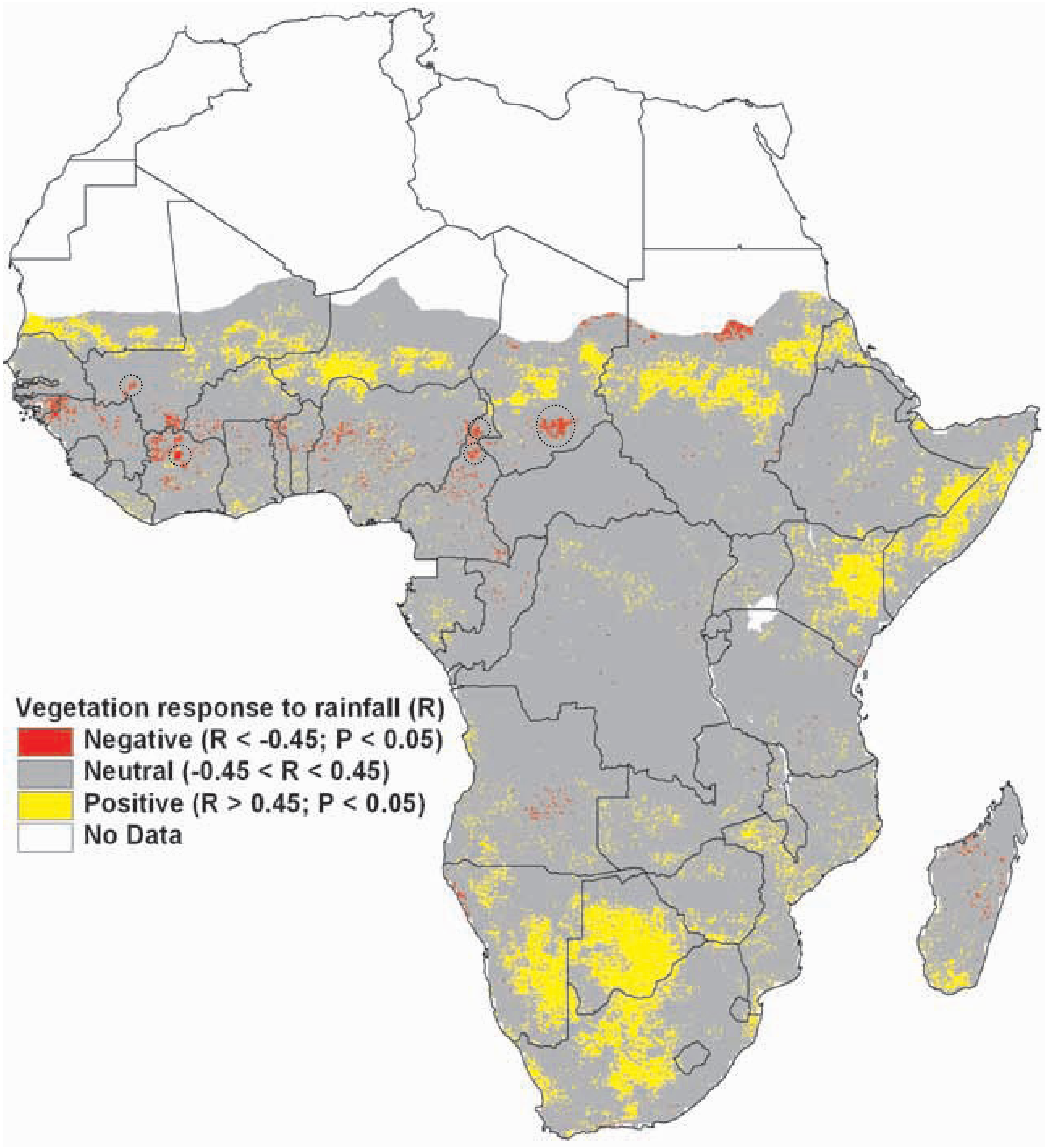
Beside the yellow area in Map 2c where vegetation significantly and positively correlated with rainfall, without offering information on the direction of the actual NDVI shifts. Areas with a significant negative correlation are shown in red. These areas may represent significantly declining vegetation 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.



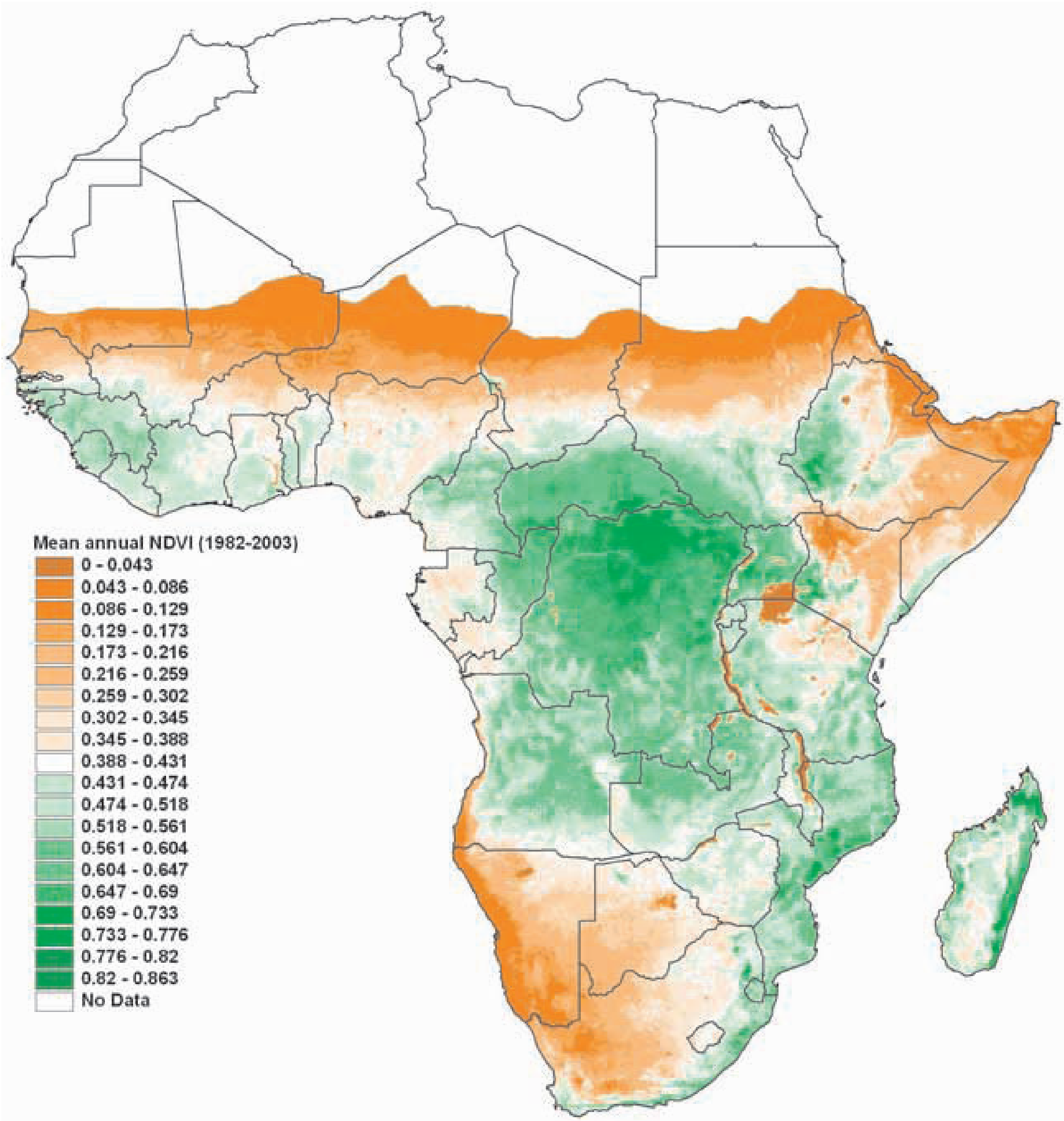
Map 2b Map of pixel-based significant test for Pearson's coefficient between annual NDVI and rainfall (R_{xy}) during the period 1982-2002.



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 km²).

Declining biomass trend	Area (km²)	%	Improving biomass trend	Area (km²)	%
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*

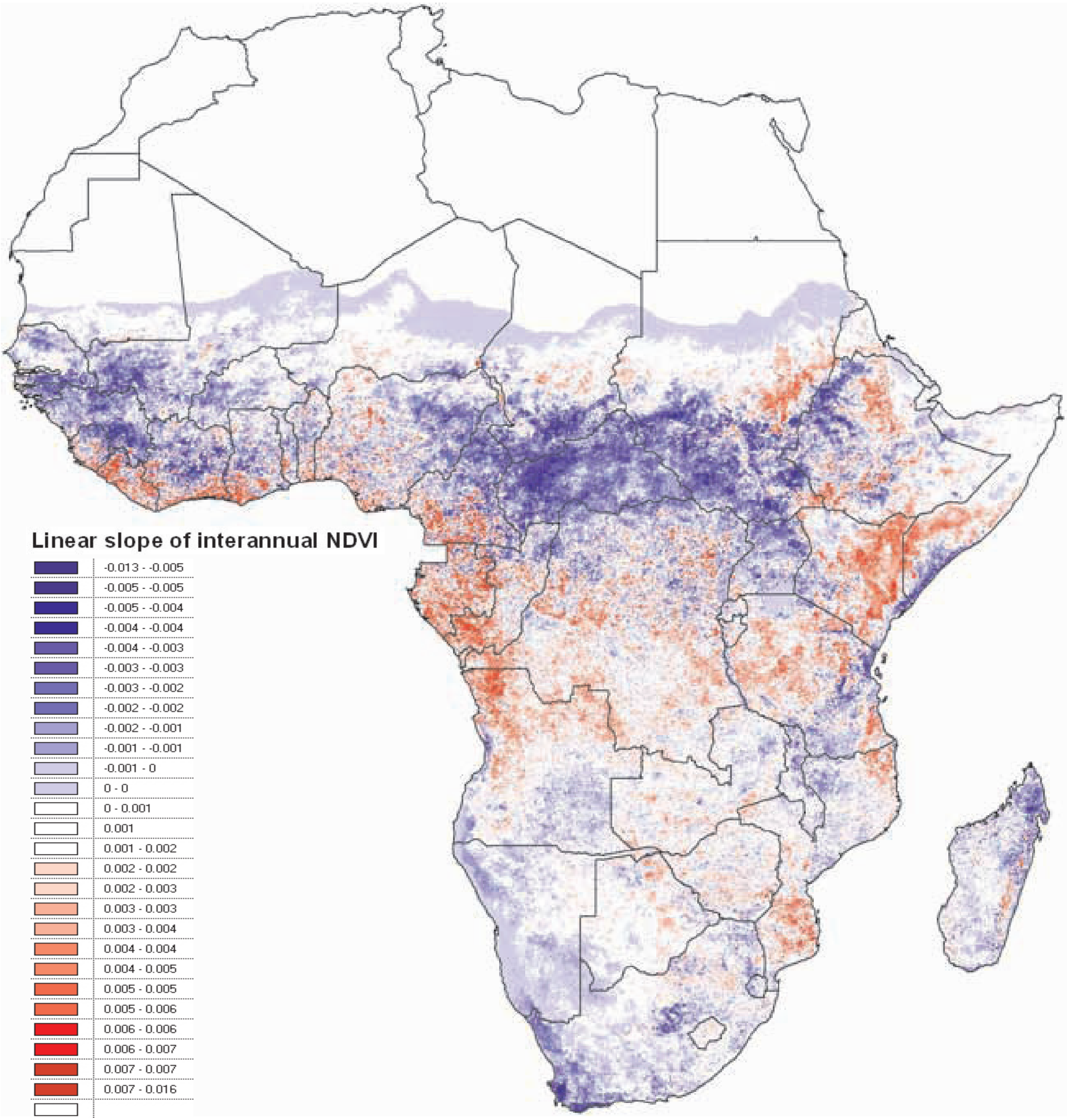
In order to obtain a better insight on where these changes in NDVI are taking place, the sub-Saharan region was subdivided in arid, semi-arid, sub-humid and humid zones and the extent of areas with declining, improving or neutral NDVI attributed to each zone (Table 6). A large proportion of the improving 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

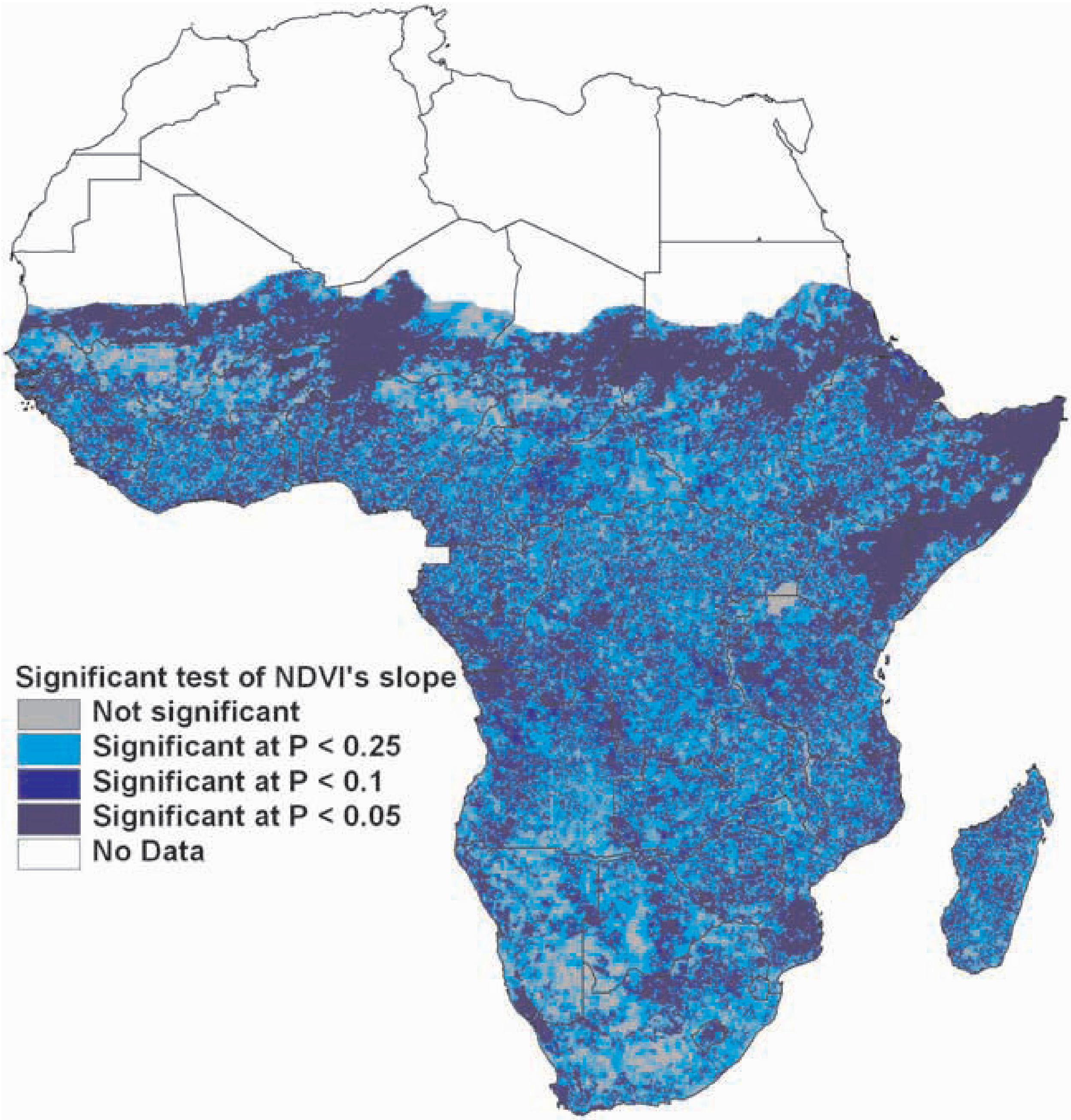
Zone of biomass trend*	Area (km^2)			
	Arid (< 500mm/yr)	Semi-arid (500 – 800mm/yr)	Sub-humid (800 – 1300 mm/yr)	Humid (> 1300mm/yr)
Declining areas	299,328	288,384	903,616	683,968
Neutral areas	2,230,400	1,502,080	2,796,480	2,214,592
Improving areas	4,210,112	1,801,792	2,492,736	1,910,208
Total area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

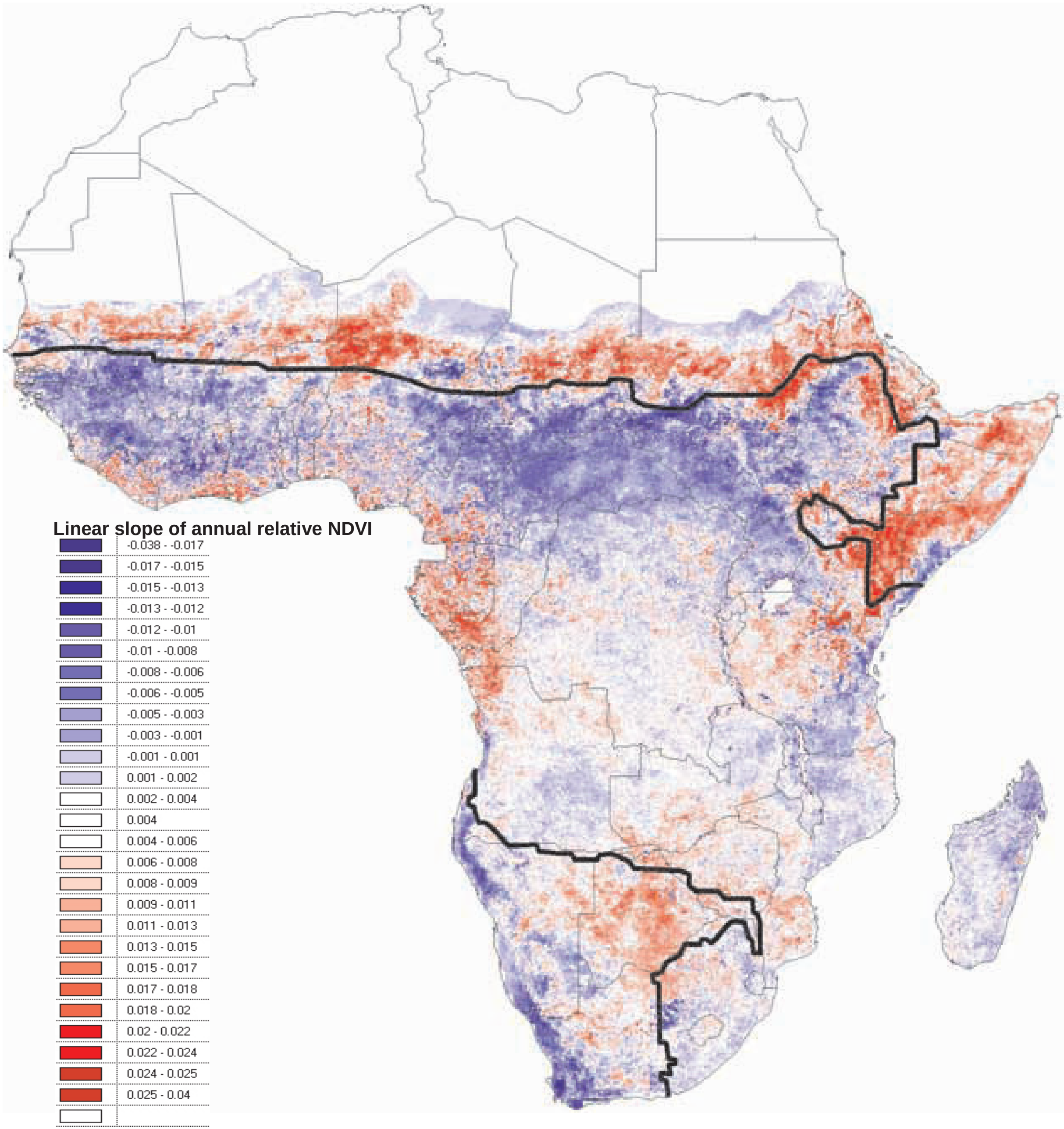
The improvement in NDVI in the wetter areas can not be easily explained by rainfall trends as no such correlation could be established (Map 2c). Though the GIMMS dataset in these regions may be unreliable due to frequent cloud covers, if the phenomenon is real, one possible explanation lays in the carbon-dioxide 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.



Map 4a Linear slope of annual NDVI (the slope *A* in the equation *NDVI* = *A*×*year* + *B*) for the period of 1982 - 2003 shows long-term trends of green biomass change.

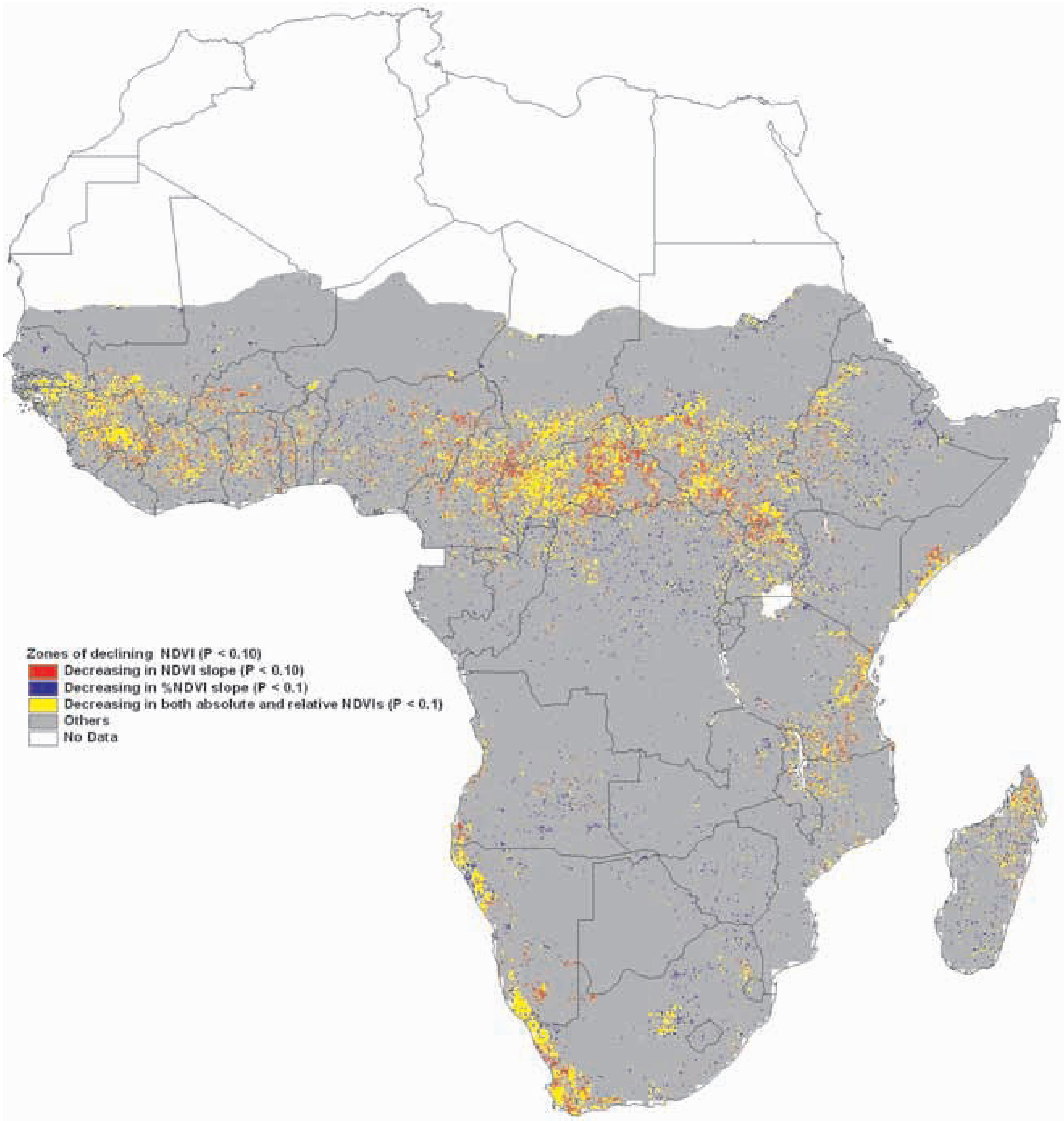


Map 4b Pixel-based significance of linear slope A (in the equation: *NDVI = A×Year + B*) over the period 1982 - 2002. (The same map for relative NDVI changes differs from this map in minor details only and is not reproduced here)



Map 4c Linear slope of annual relative NDVI (the slope coefficient A_r in the equation $\%NDVI = A_r \times year + B$) for the period of 1982 – 2003, showing long-term trends of green biomass change compared to the initial status (1982) at each pixel. Note: for each pixel, the relative NDVI of year *i* was calculated as: $\%NDVI_i = NDVI_i \times 100 / NDVI_{1982}$, where $NDVI_i$ and $NDVI_{1982}$ are the absolute NDVI values of years *i* and 1982, respectively. The bold black lines are the 500 mm yr^{-1} isohyets averaged for the same period.

The focal areas of long-term degradation in NDVI, whether in absolute or relative terms, are summarized in Map 5. Long-term degradation areas are pixels with a negative slope of either absolute or relative annual NDVI ($A < 0$ or $Ar < 0$), and a significance at 90% confidence ($P < 0.1$). Significant degradation pixels were identified by overlaying Maps 4a and 4c with their respective significance maps. It should be recognized, that although in the dry parts of Africa large regions are actually greening due to improving climate, parts of this region may suffer from human-induced degradation which is masked by this greening trend. Thus, the extent of degradation shown in Map 5 might be somewhat underestimated due to masking by climatic improvements or CO^2-or NOx-fertilization.



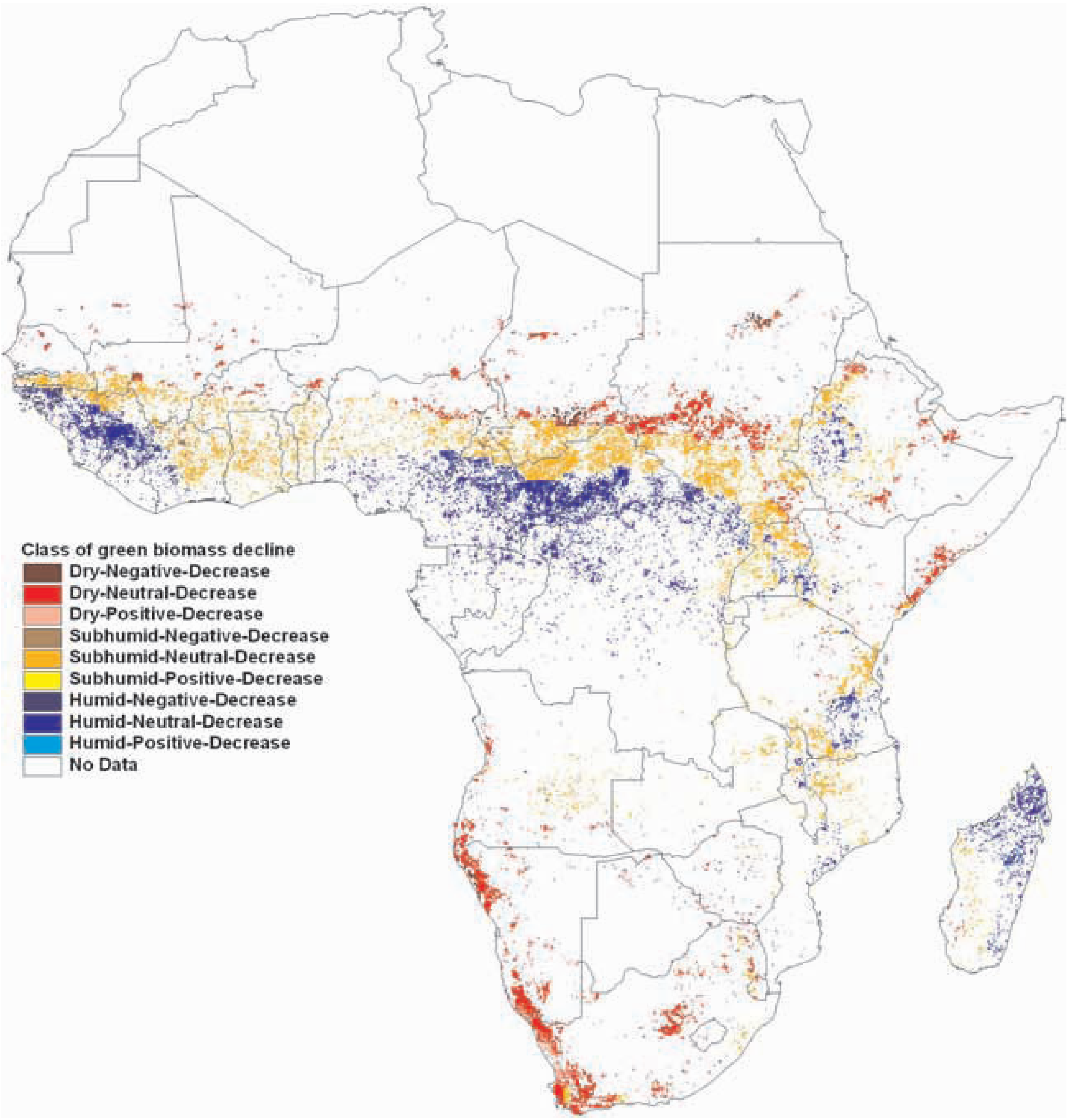
Map 5 Map showing areas of long-term degradation in green biomass. The significant degradation areas will be used as the boundary to formulate different degradation classes in the follow up steps.

4.4 Mapping vegetation degradation

The area on Map 5 that is only discernable when looking at NDVI in relative terms comprises about 400.000 km^2 (shown in blue). The area that is significantly losing vegetation cover only in absolute NDVI terms is of similar magnitude (in red) whereas the area declining in both covers 1.4 million km^2 (yellow). The difference in the significant absolute or relative loss in NDVI is not obvious, so that for the purpose of identifying hot spots of degradation, all coloured areas on Map 5 are considered to be of equal importance. The analogue overlay of the thematic maps for climate zones (Map 1, with 3 classes), long-term vegetation response to rainfall (Map 2c, with 3 classes) and long-term vegetation degradation (Map 5, reconciled to 1 class) produces 9 composite classes of climate-vegetation change (Table 4) which are shown in Map 6.

We calculated the areas showing significant vegetation changes over time as represented in Table 7. Of the 2.18 million km^2 territory showing a significant (absolute or relative) decrease in NDVI, 94% is not affected by inter-annual changes in rainfall (shown in bold letters). This region does not appear to be affected by climate change and should be reflecting the human impact on vegetation. In addition, there are some areas that have a negative correlation with rainfall and are decreasing in NDVI in spite of an increase in rainfall, adding an additional 4% as degrading land that are of particular concern. The remaining 2 % (shown in lighter shaded colour) are areas with decreasing NDVIs but with NDVI positively correlated with rainfall). These are regions where the declining vegetation is likely due to reduced rainfall and in which any human induced causes may not be discernable.

For the remainder of this analysis we will focus on the region with declining NDVI (absolute or relative), with a neutral or negative response to annual rainfall representing the region that is subjected to human-induced vegetation degradation, an area of around 2.13 million km^2. Map 6 (the 2 darker shades of blue, yellow and red) shows the areas with long-term vegetation decline for different rainfall zones, indexed by categories (Dry, Subhumid and Humid). In these areas, annual NDVI was significantly decreasing over the last 22 years (1982-2003). Because the correlation coefficients between annual NDVI and precipitation are negative, poor (category Neutral: $|Rxy| < 0.45$) or not significant, there is no reason to assume that rainfall change was the cause of this long-term vegetation decline.



Map 6 Nine composite classes of vegetation degradation that combine climate (Map 1), vegetation response to rainfall (Map 2c) and long-term green biomass decline (Map 5). The lighter shades of color are likely reflecting decreasing vegetation in response to reduced rainfall and are eliminated from further analysis.

Table 7 Area (km^2) of composite classes in Map 6. The areas with positive correlation between NDVI and rainfall (in gray) were considered not due to human activity (Map 2c).

Class	*Area (km^2)*	*%*
Dry-Negative-Decrease	28,544	1
Dry-Neutral-Decrease	**528,443**	**24**
Dry-Positive-Decrease	35,078	2
Subhumid-Negative-Decrease	42,822	2
Subhumid -Neutral-Decrease	**854,333**	**39**
Subhumid -Positive-Decrease	8,954	0
Humid-Negative-Decrease	24,188	1
Humid-Neutral-Decrease	**654,332**	**30**
Humid-Positive-Decrease	6,014	0
Total degraded area	*2,182,707*	*100*

Note: Classes with grey boxes are likely losing vegetation due to change in rainfall and are eliminated from further analysis.

5 RELATIONAL ANALYSIS OF LAND ATTRIBUTES AND VEGETATION DECLINE

In the following section the results of the observations made from space and the monitoring of rainfall, culminating in Map 7, are related to some of the other attributes of the land, stored in databases held by different organizations. The expectation is that such an analysis may help set priorities on the territories that should be given research attention or that should be subjected to immediate remedial action, or, in extreme cases should be abandoned. It is recognized that the value of such analysis is directly related to the quality of the respective databases, which in some cases may be questioned. However, the analytical framework retains its validity and can be easily re-applied whenever better databases become available.

5.1 Population

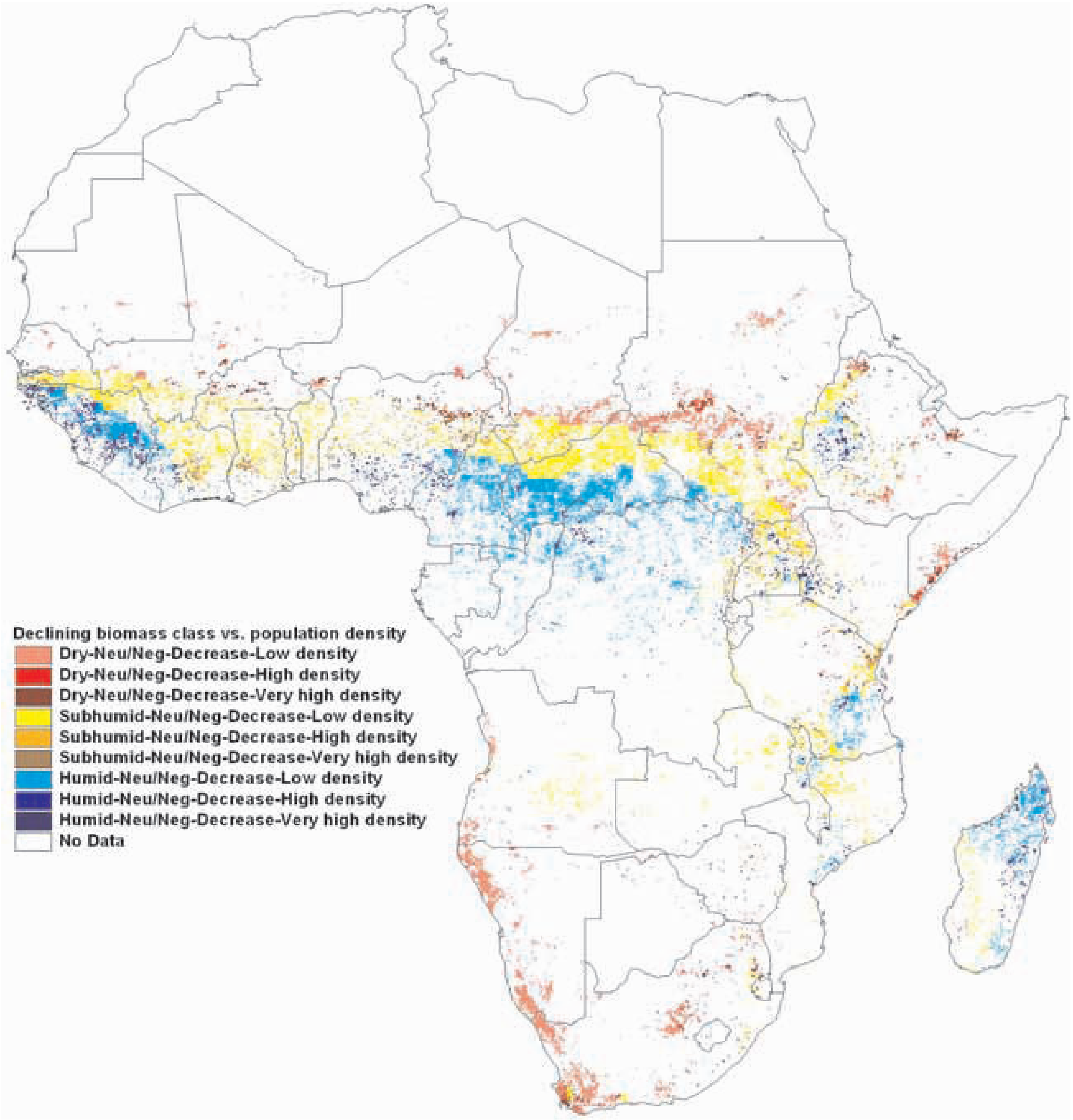
The first question asked was whether the areas of degradation were associated with regions where population pressure is high, as suggested by the GLASOD analysis. The mean population densities for the 1980 – 2000 period (average of 1980, 1990, and 2000) were obtained from the Grid Population of the World Version 3 (GPWv3) dataset of the Center for International Earth Science Information Network (CIESIN) at Columbia University and Centro Internacional de Agricultura Tropical (CIAT) (CIESIN/CIAT, 2004).

The mean population densities for the three climatic zones are 14 pers/km² for the dry zone, and 31 and 28 pers/km² for the sub-humid and humid zone, respectively (Table 6). The pixels in these rainfall zones that are showing signs of vegetation degradation (declining NDVI) over the past 2 decades that can not be attributed to decline in rainfall have average population pressures of 15, 27, and 25 pers/km², respectively, very close to those for the rainfall zones as a whole. In order to see how the population is distributed within the degrading zones, each of the degrading pixels of the respective rainfall zones was differentiated according to three classes of population density (smaller than the mean, more than twice the mean and between these two) as shown in Table 8.

Table 8 Population density in main climate zones[1)] and in the areas with decreasing NDVI (biomass) not attributable to declining rainfall[2)] within them (see Table 7). Right hand column provides classification of population densities for further analysis[3)] (see text).

Climate[1)] zone	*Population density (pers/km²)*	*Zone with biomass decrease in relation to rainfall[2)] (Table 7)*	*Population density (pers/km²)*		
			Mean	*Population classes[3)]*	
Dry	14	*Dry-Negative and Neutral*	15	Low density:	< 15
				High density:	15 - 30
				Very high density:	> 30
Subhumid	31	*Subhumid- Negative and Neutral*	27	Low density:	< 27
				High density:	27 - 54
				Very high density:	> 54
Humid	28	*Humid- Negative and Neutral*	25	Low density:	< 25
				High density:	25 - 50
				Very high density:	> 50

A further stratification of the rainfall regions that are in vegetative decline (Map 6) based on population density is depicted in Map 7. This map clearly shows that most of the degrading areas are low-density in population for each of the respective rainfall zones. These regions possibly constitute marginal or fragile lands with limiting carrying capacities that are easily over-populated. However, there are some areas where vegetation decline is strong and population density is high, notably South Western Ethiopia, the Ugandan highlands, Northern Nigeria and South Eastern Sudan. The higher population densities are commonly found on the best and most resilient land, and these areas should be given high priority for restoration investments once the cause of degradation has been established. In case nutrient depletion is the cause, these areas could be targeted with fertilizer marketing schemes as such inputs are likely to be economical in such regions (Kaizzi et al., 2006). In the case of erosion, investments would be needed to slow run-off (Tamene, 2006). The more marginal areas where the carrying capacity is low to begin with are likely to suffer more as population density continues to increase unless (public) measures are taken to increase the carrying capacity of these regions and reverse or protect them from further degradation. There where such measures are not economically sustainable, the aim might have to be to reduce the pressure on the land by offering alternative ways out of poverty.



Map 7. Green biomass decline in different climate zones that is not attributable to rainfall decline- (neu/neg Table 7) in relation to population density showing most of the declining zones to be with relatively low population density.

5.2 Terrain and soil constraints

In a next step, sub-Saharan Africa was differentiated according to the topographic and soil based suitability of the land for agriculture using FAO and USGS databases. Topographic SRTM (Shuttle Radar Topography Mission) elevation data with a pixel resolution of 1 km derived from USGS (2004) is shown in Map 8a. Pixels with elevation > 3500 m a.s.l or surface slope > 25° are considered not suitable for agriculture (see Sheng, 1990), and are not considered prime subject for further research. The bad terrain (yellow) for agriculture will require special precautions and cultivation techniques to prevent rapid degradation. The extent of such land in sub-Saharan Africa is rather limited. The remaining part of sub-Saharan Africa is considered good agricultural land (blue).

Good: 0° ≤ slope ≤ 15° and elevation ≤ 3500 m a.s.l (green)

Bad: 15° < slope ≤ 25° and elevation ≤ 3500 m a.s.l (yellow)

Unsuitable: slope > 25° or elevation > 3500 m a.s.l (red)

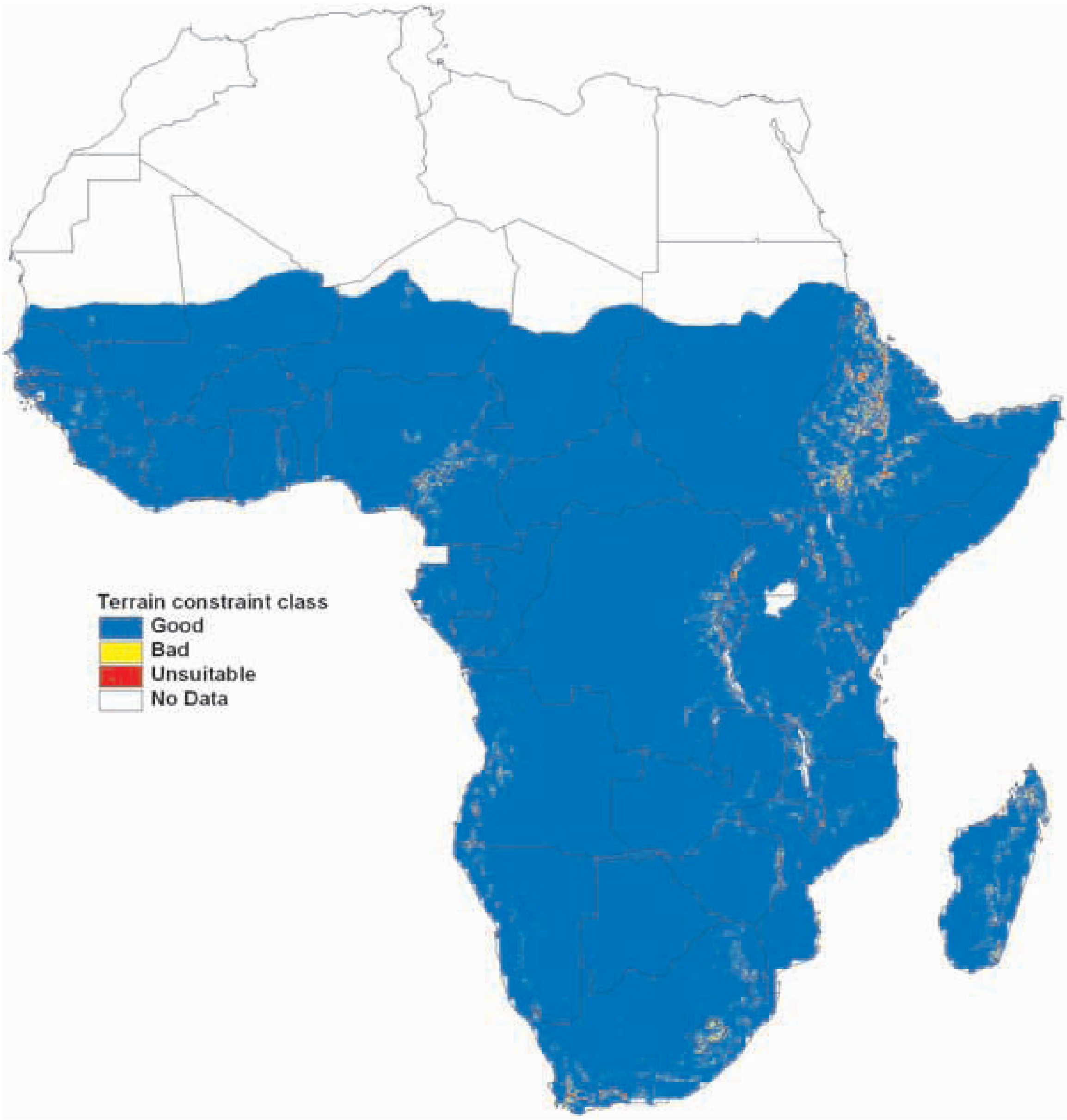
Similarly, soil constraint classes were derived from the FAO classification of soil constraints (Fisher et al., 2002) by aggregation as follows:

Good: FAO class 1 or 2 (blue)

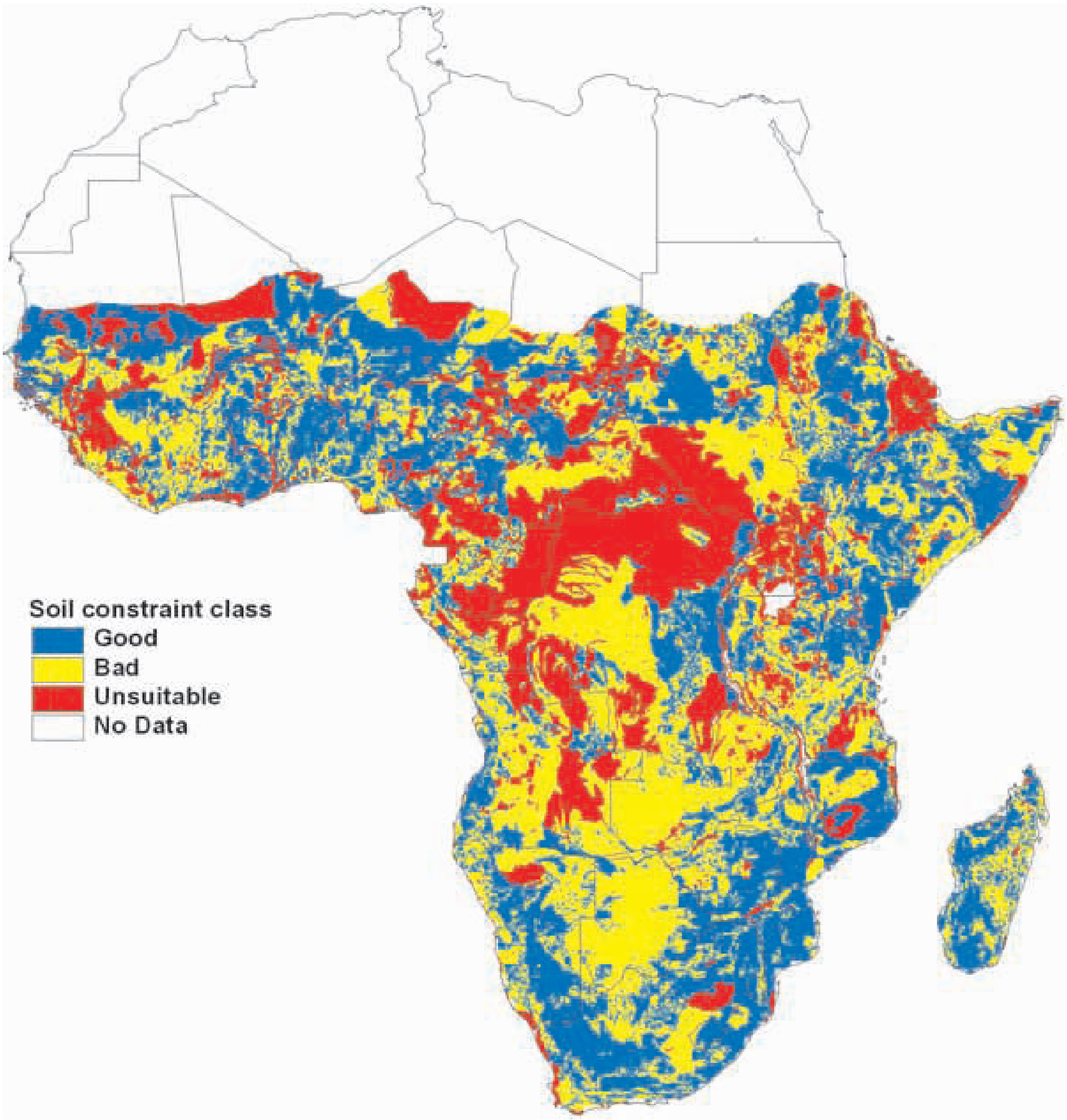
Bad: FAO class 3 or 4 (yellow)

Unsuitable: FAO Class 5, or 6, or 7, or 8 (red)

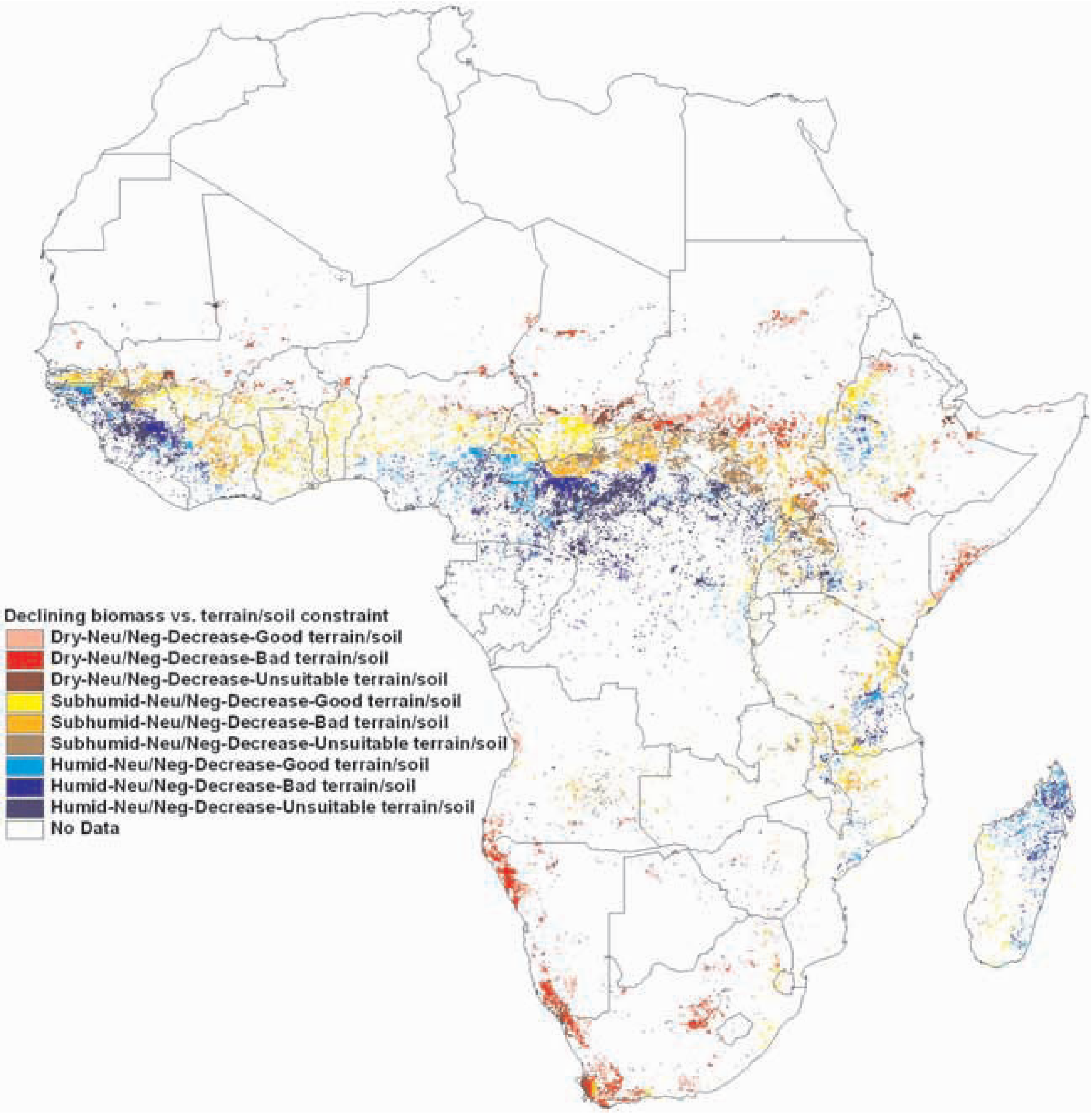
which are shown in Map 8b. Pixels in the degraded areas with very severe soil constraints (Unsuitable) include uncultivable land due to such problems as high salinity or laterite crusts and require little research attention, as investments in these lands offer little in return. Even for the regions with inherently bad soils, the economics of soil improvement may not always be favourable.



Map 8a. Terrain constraints with respect to agriculture production.



Map 8b. Soil constraints with respect to agriculture.



Map 9. Human-induced green biomass decline on land with different soil/terrain constraints.

The human-induced green biomass decline area of Map 6 can thus be redrawn by classifying the areas according to terrain and soil suitability for agriculture as shown in Map 8a,b which renders Map 9. Those areas that are unsuitable for agriculture due to topographical or soil constraints comprise about 0.68 million of the 2.13 million km^2 that were considered subject to degradation and most of it lays in the regions with relatively low population density, particularly in the sub-humid and humid regions (Table 9). Such areas, if no longer under protective vegetation, should be re-vegetated in order to restore ecosystem services. Erosion from such regions can cause damage to reservoirs and agricultural land downstream.

Table 9 Area (km^2) of terrain and soil constraint classes calculated for each degradation class.

Degradation class	*Total area (km^2)*	*Terrain constraint**			*Soil constraint***		
		Good	*Bad*	*Unsuitable*	*Good*	*Bad*	*Unsuitable*
Dry-Neutral/Negative-Decrease - Low density	*450689*	442751	5760	2178	177084	194302	79291
Dry-Neutral/Negative -Decrease - High density	*44794*	43899	702	194	22397	16190	6207
Dry-Neutral/Negative -Decrease - Very high density	*61492*	59968	1210	315	28157	26693	6655
Subhumid-Neutral/Negative -Decrease - Low density	*685247*	674817	7611	2819	202373	269249	213638
Subhumid-Neutral/Negative -Decrease - High density	*106879*	104387	1597	895	44092	38405	24382
Subhumid-Neutral/Negative -Decrease - Very high density	*105016*	101059	2747	1210	47674	35973	21381
Humid-Neutral/Negative -Decrease - Low density	*541124*	529218	9983	1924	113982	160833	266309
Humid-Neutral/Negative -Decrease - High density	*60669*	58685	1283	702	16129	19203	25350
Humid-Neutral/Negative -Decrease - Very high density	*76738*	74113	2239	387	32767	21756	22204
Total	*2132649*	*2088896*	*33130*	*10624*	*684654*	*782604*	*665415*

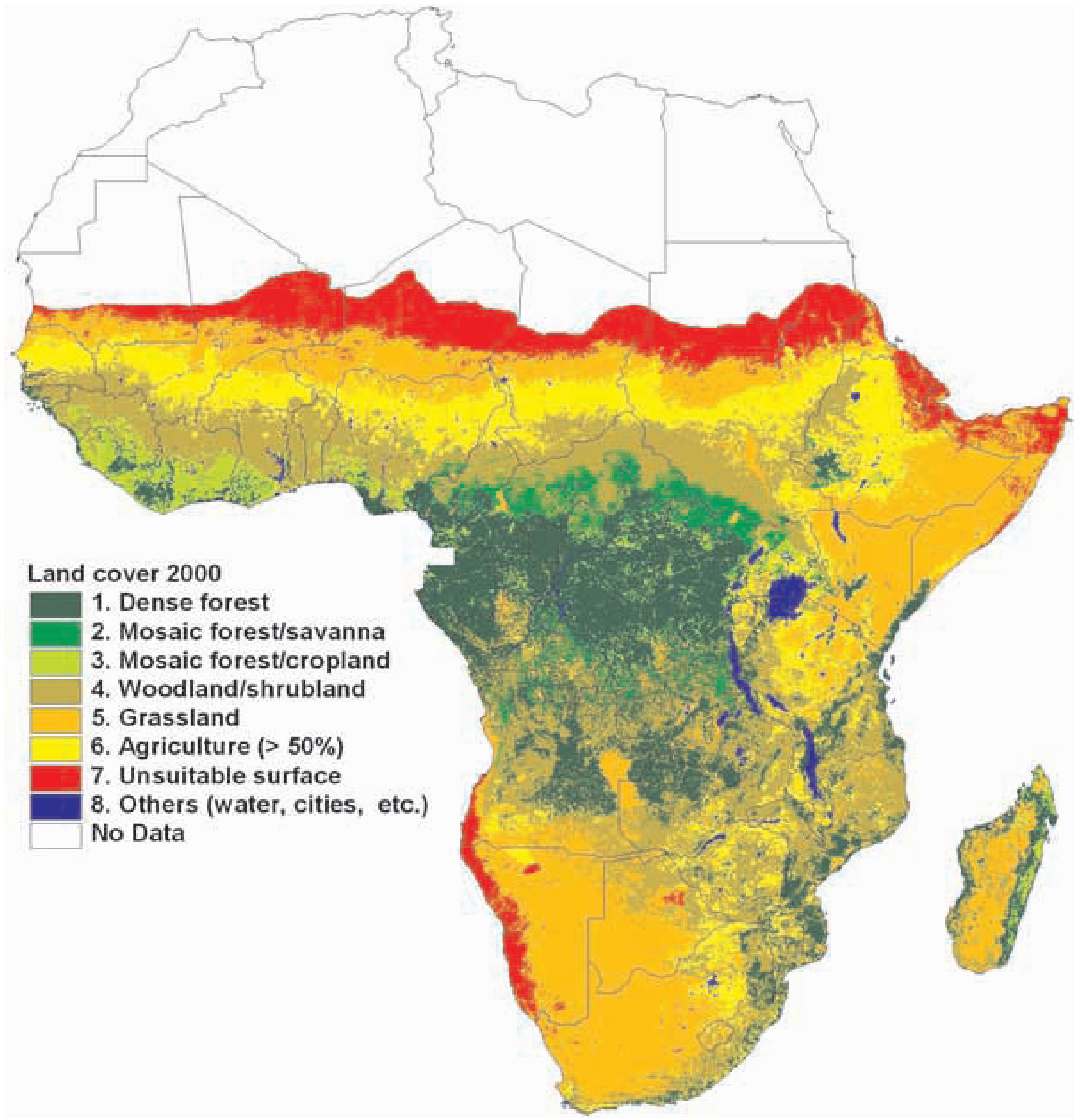
Note: * Terrain constraint classes with respect to agricultural production:
Good: 0° ≤ slope ≤ 15° and elevation ≤ 3500 m a.s.l
Bad: 15° < slope ≤ 25° and elevation ≤ 3500 m a.s.l
Unsuitable: slope > 25° or elevation > 3500 m a.s.l (eliminated in this study)
** Soil constraint classes were regrouped from FAO's classes of all soil constraints:
Good: Class 1 or 2 in FAO's classification
Bad: Class 3 or 4 in FAO's classification
Unsuitable: Class 5, or 6, or 7, or 8 in FAO's classification (eliminated in this study)

From Table 9 it is clear that degrading land unsuitable for agriculture is largely due to unsuitable soils, as the extent of land with unsuitable topography constraints is negligible. The remaining 1.45 million km^2 region with vegetation decline is found on potentially cultivable land and covers a band that extends from West Africa to Ethiopia. Some of these regions are considered the breadbaskets of Africa. Moreover, over half of this degrading (potentially) arable region is on poor quality soils. Economic returns on research investments may be more difficult to achieve in this region. The question to answer now is: what are the degrading areas actually being used for?

5.3 Land use and land cover

In order to obtain a better insight into where exactly this degradation is occurring, the entire land degradation map was cross referenced with the land use/land cover map of GLC2000. This allows differentiation of the degradation area according to land use type. Actual land use and land cover for the year 2000 was extracted from the GLC2000 data (Mayaux et al., 2004), and is shown as Map 10. It shows 8 major classes, two of which cover agriculture (3 and 6) and one pastoralism (5). This dataset is developed by the Joint Research Center (JRC) of the European Commission (EC) in partnership with more than 30 institutions around the world, using Satellite Pour l'Observation de la Terre (SPOT) VEGETATION 1-km satellite data. The quality of the map was verified using different approaches and based on data from different sources such as ground observations, national forest statistics, previous land cover maps, and high resolution satellite imagery (Achard et al., 2001; Bartalev et al., 2003; Tateishi, 2002; Cihlar et al., 2003; Fritz et al., 2003; Mayaux et al., 2004). Its quality has also been compared with other global land cover maps from different sources and employing different methods (e.g. Giri et al., 2005).

Superimposing Map 10 on Map 9 allows the development of Map 11 in which the areas with vegetation decline are categorized as suitable for agriculture and actually cultivated (brown) or not cultivated (blue). The non-cultivated areas are predominantly in grasslands and mosaic/forests. Also indicated are regions that are considered unsuitable for agriculture but are, in fact, being cultivated (red). The latter are found, for instance, on the eastern borders Sierra Leone and Liberia as well as in Uganda. Cultivating such marginal areas is likely to do more harm to the environment than it profits the farmers, and such areas should probably be rehabilitated to their natural condition as soon as possible.

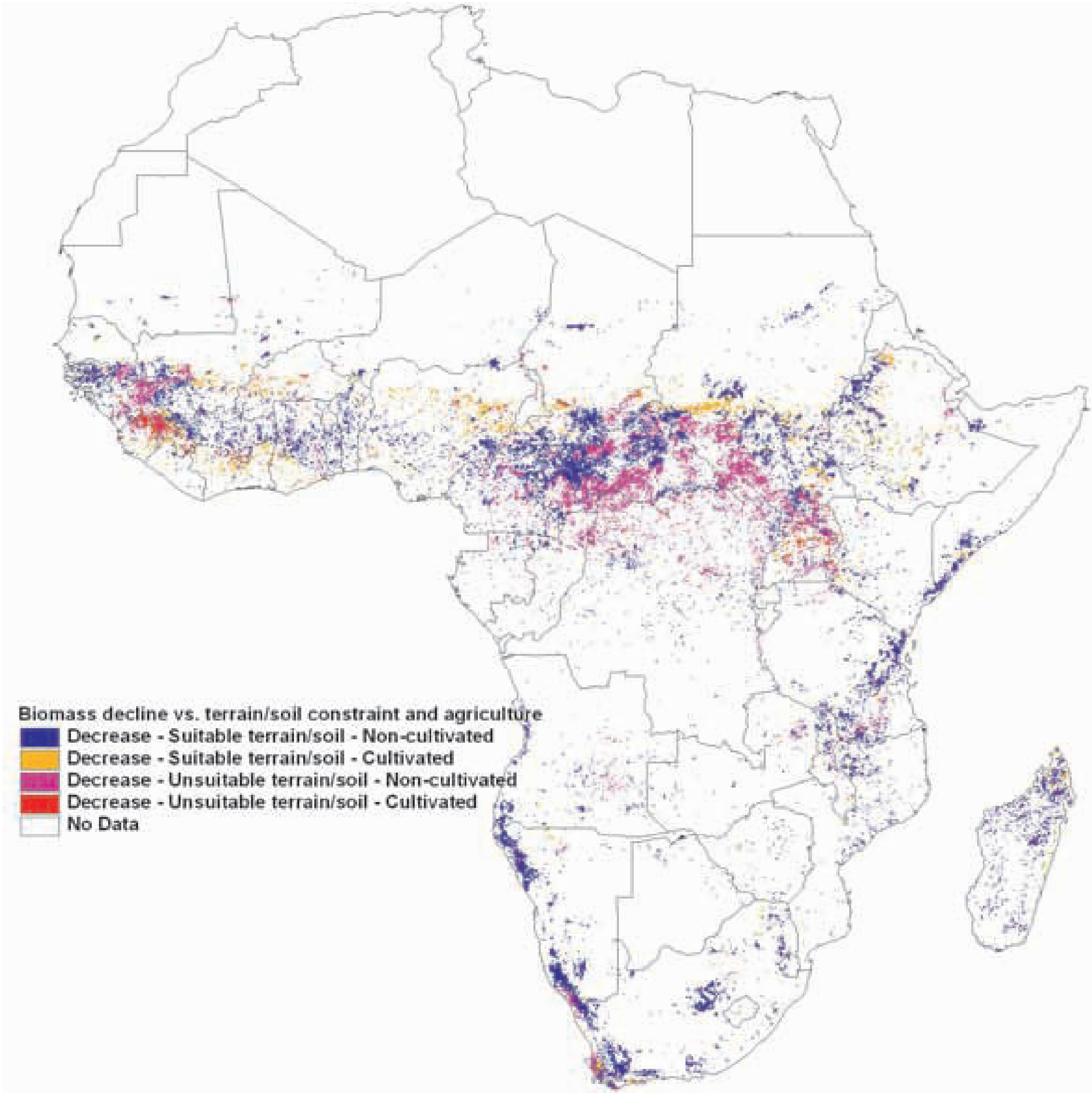


Map 10. Major land-cover classes in 2000 extracted from GLC2000 data (Mayaux et al., 2004).

The statistical details of the degrading region by land-cover/use, as summarized in Map 11, are shown in Table 10. In total, about 9.4 % of the SSA region or 2.13 million km^2 is suffering from significant biomass decline. Out of the 2.13 million km^2 suffering from significant vegetation decline (Table 10), 0.68 million km^2 are not suitable for agriculture of which 80 thousand km^2 are actually being farmed and probably should not be. Means should be found to offer alternatives to these farmers so that land can be restored over time. In the dry areas, this is agricultural land whereas in the more humid regions these are the forest-cropland mosaics. Most probably these areas should be turned into exclusion zones or actively restored to their native vegetation. Of the remaining 1.45

million km^2 that are in decline but suitable for cultivation, 0.4 million km^2 are actually farmed (agriculture and forest/cropland) and are likely over-exploited or poorly managed. The area is equally divided between land with good and bad soils, except for the humid forest/cropland zone, where the bad soil/terrain areas appear to be more vulnerable. These agricultural regions require considerable research efforts in order to identify the immediate and proximate causes for their decline and to develop more sustainable farming practises.

As is seen in Table 10, a quarter million km^2 of the area under grassland, largely in the dry areas, shows a decline in vegetation, likely due to over-grazing. Of the 5.5 million km^2 of grassland in SSA, this quarter million km^2 constitutes only 5%, three-quarter of which (195 thousand km^2) are found in the dry areas where they may be affected by livestock grazing. Not surprisingly, the woodland/shrublands are most in decline in the sub-humid tropics where they are predominant, whereas the forest/savanna and dense forests are threatened in the humid areas. As much as 16% of the woodland/shrubland is in decline, probably reflecting encroachment by farmers on these natural habitats. For the expansive, more densely forested regions, the degrading area amounts to 10% of the region, most of which is unsuitable for agriculture. This may be the region of most intensive deforestation.



Map 11. Areas with biomass decline as function of soil/terrain constraints and their agricultural use. Note: (1) suitable soil/terrain includes good and bad soil/terrain conditions as in Maps 8a and 8b, and (2) cultivated land as from GLC2000 data (i.e., categories 3 and 6 in Map 10).

Table 10 Area of land-use/cover types calculated for each degradation class across soil/terrain constraints.

Degradation class	*Area of land-use/cover type (km²)*							*Total area (km²)*
	Dense forest	*Forest/ Savanna*	*Forest/ Cropland*	*Woodland/ Shrubland*	*Grassland*	*Agriculture*	*Others*	
Dry-Neutral/Negative-Decrease –Good soil/terrain	8059	448	0	33021	95614	52538	35078	*224758*
Dry-Neutral/Negative-Decrease -Bad soil/terrain	2299	61	61	48896	81022	55745	49283	*237366*
Dry-Neutral/Negative-Decrease -Unsuitable soil/terrain	702	61	61	27261	18307	29185	18428	*94005*
Subhumid-Neutral/Negative-Decrease -Good soil/terrain	22591	4102	10684	186243	9862	51836	1912	*287230*
Subhumid-Neutral/Negative-Decrease-Bad soil/terrain	24261	15173	15803	224963	11580	51195	3328	*346302*
Subhumid-Neutral/Negative-Decrease-Unsuitable soil/terrain	13189	9595	10563	186364	2880	22784	17400	*262776*
Humid-Neutral/Negative-Decrease -Good soil/terrain	31484	18053	17085	59774	17787	10370	714	*155267*
Humid-Neutral-Decrease/Negative–Bad soil/terrain	54341	29633	32646	71487	10817	6655	762	*206341*
Humid-Neutral-Decrease/Negative-Unsuitable soil/terrain	90302	87168	37244	84797	5251	4804	6534	*316100*
*Total area within biomass declining zone**	*247227*	*164294*	*124146*	*922807*	*253120*	*285112*	*133439*	*2130145*
Total area within SSA	*3370310*	*676922*	*808316*	*5729725*	*5559684*	*3211836*	*2323648*	*21680441*

* Differences between the total area of each land cover in this table and Table 4 are due to the edge errors. The error of total area is about 14 pixels (64 km^2/pixel). The error of "Others" category is about 8 pixels, and those of other categories are less than 3 pixels each.

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6. Summary and Conclusions

The objective of this study was to identify areas of land degradation in sub-Saharan Africa as observed from space by tracking the greenness of the vegetation signal expressed as NDVI over time. This study has utilized a series of existing databases and, through successive comparison of these, draws conclusions related to recent degradation of land in sub-Saharan Africa. Vegetation decline based on mean annual NDVI was used as a proxy for land degradation. The datasets (based on 8×8 km^2 pixels) of weather and NDVI-derived vegetation dynamics were averaged annually from monthly observations over the last two decades of the 20th century. This is likely to have captured reduced agricultural productivity as well as loss in native vegetation cover. First, we divided sub-Saharan Africa in dry (mean annual precipitation MAP <800 mm.yr-1), sub-humid (800 mm.yr-1 <MAP<1300 mm.yr-1) and humid dry (MAP >1300 mm.yr-1) regions, yielding three zones of similar geographic extent. In a second step we identified the regions where the annual vegetation reacts significantly to changes in mean annual rainfall conditions. For those with positive correlation, vegetation dynamics are affected by climate change (or cycles) and these are not suitable to identify human induced degradation. This excluded less than 2% from further analysis. In those with negative correlations the land shows either declining biomass despite improving rainfall suggesting serious degradation, or improving biomass despite a decline in rainfall. The latter is most likely due to human actions such as aforestation or irrigation (e.g Northern Sudan). These areas were relatively small (95.000 out of the 2.18 million km^2).

Subsequently the slope and the significance of the vegetation index (NDVI) over time were considered. Areas not showing a decline or increase in this vegetation index (NDVI), either in absolute or in relative terms, were considered stable vegetation covers. Those that showed an increase in vegetation index were predominantly found in the pastoral zone below the 500 mm isohyets and revealed a "greening of the Sahel" in the period evaluated. This has also been reported elsewhere. This region largely coincides with the region where NDVI fluctuations were positively correlated with rainfall which was excluded from this analysis of human induced land degradation. Large areas in of SSA showed a positive NDVI trend not related to rainfall. One possible explanation would be the CO^2 and NOx fertilization due to increased levels in the atmosphere. The areas that show a consistent and significant decline in NDVI (or land degradation) over time amounts to around 2.13 million km^2 or 10% of the SSA land mass. The characteristics of this area were analyzed in more detail.

Over 60 million people live on land that is losing its ability to produce green biomass presumably due to human activity. For each rainfall zone, the mean population densities in areas with declining vegetation were more or less the same as for the rainfall zone as a whole. However, the large majority of the declining areas is thinly populated, irrespective of the rainfall zone. This would suggest that these are marginal areas with limited bearing capacities to start with. The GLASOD study found for sub-Saharan Africa that land degradation at the time was more or less linearly correlated with population density. The conclusion from this study is more nuanced. Most of the land that is degrading is doing so with below average population densities. These regions are likely to get worse or will spread further as population continues to increase in most of sub-Saharan Africa. Donors should carefully analyze the sustainability of continued agricultural land use before embarking on measures or investments in agriculture to alleviate poverty in these regions. Some of these lands may be best taken out of cultivation. However, this study also identifies some degrading areas with high population densities. Often these are regions with high productive potential and in urgent need of remediation. It is here that fertilizer schemes and land conservation measures should be targeted as they are likely to be economically feasible.

A dataset derived from the FAO was used to delineate areas with different topographical and soil constraints. These datasets were overlaid on the map with the declining vegetations. For the terrain constraints, slopes over 25% and areas over 3500 m a.s.l. were considered unsuitable. Similarly, soil constraint classes 5 through 8 in the FAO classification were considered inappropriate for agriculture. The former covers less than 10.6 thousand km^2 and is negligible, but the latter cover nearly 0.67 million km^2 of the degrading area. Most likely farmers are occupying such marginal land due to land scarcity. Once denuded, such land is often not productive and exposed to the elements, causing water or wind erosion. Farmers seeking new land that move into such areas may do more harm to the environment than they do themselves good. The donor community should seek ways for these farmers to avoid occupying such land as remediation is difficult and costly. Nearly half of the remaining degrading land is on soils that are of rather poor quality. These soils may not easily be ameliorated and might never gain the resilience that good farm land requires.

In order to obtain a better insight into where exactly this degradation is occurring, the emerging land degradation map was cross referenced with the land use/land cover map of GLC2000. This allows differentiation of the degradation areas according to land use type. Of the 0.67 million km^2 that are not suitable for agriculture, 105 thousand km^2 are actually being farmed and probably should not be. Means should be found to offer alternatives to these farmers so that land can be restored over time. Of the 1.46 million km2 that are degrading but suitable for cultivation, 0.3 million km2 are actually farmed (agriculture and forest/cropland) and are likely over-exploited or poorly managed. Moreover, half of these are on poor soils and it may be too costly to restore such land. These are areas where considerable research efforts should be made to identify the immediate and proximate causes and develop more sustainable farming practises. A quarter million km^2 is under grassland, largely in the dry areas and most likely is being over-grazed. Nearly 1.09 million km^2 are under woodland/shrubland and forest/savanna, which each might be losing native trees as land

The fraction of the land showing significant decline in vegetation cover is relatively modest (around 10%). This would correspond with the fraction of SSA with "very severe" land degradation symptoms in the GLASOD assessment of late eighties. However, it is unlikely that any direct comparison between these two studies can in fact be made. It is more likely that these areas are additive, as the very severely degraded land from the GLASOD study would not likely show great further vegetation decline. The creeping additional loss of 10% over the last 20 years of the past century, if the pace is not slowed, translates into serious trouble for sub-Saharan Africa in the course of the current century.

It may be reasonable to assume that, when land degradation can be observed from space through declining biomass production, particularly on agricultural land, the underlying degradation processes must indeed be rather severe. Even though the extent of degradation from this assessment appears modest, much more degradation is likely to be on-going without being detectable (yet) with satellites. Moreover, land degradation on agricultural land seems to be taking place in the most productive areas of sub-Saharan Africa, threatening food production in the long run. Finally, this land degradation is happening against a background of increasing population and deteriorating climate conditions in a food insecure part of the world.

This assessment can only be seen as a first approximation, and the maps and assessments made here need further verification in the field. The analysis, in essence, is as good as the underlying databases. However, as better data becomes available the analysis framework proposed here allows for easy substitution of this information and rapid generation of a new assessment. As it stands, the following conclusions can be drawn that affect the research community:

- In the absence of any instruments for monitoring the rate of land degradation on the ground in SSA, satellite-based systems offer the best hope for tracking the state of this vital natural resource on this vast continent. A systematic research effort should be made to verify the validity of the findings reported here and to refine the analytical tool and interpretation of the results. As more and better data-bases are placed in the public domain the current study should be updated periodically.
- The current mapping exercise should be used to identify application domains, areas with common climatic, vegetation, physiographic and soil and land use characteristics that appear to be threatened by human induced land degradation. Based on this stratification, research organizations should be able to select pilot research sites where in-depth research can be undertaken to assess the total cost of land degradation (including the valuation of loss of ecosystem services) and design sustainable land management options that will maximize social benefits from the use of the land.
- Research should be undertaken to study the institutional arrangements around land access and tenure within the application domains in order to find means that will allow sustainable land management systems to be established equitably. In some cases this will be possible only through payment for ecosystem services (PES) for which the level and beneficiaries need to be determined. The use of such instruments should be an integral part of the strategy to preserve the land for future generations.

However, some of the regions identified in this study deserve immediate attention from the donor community and policy makers:

- Identify those agricultural regions where soil and terrain conditions seem so unfavourable that immediate action is required to restore the land to its natural condition. Donor agencies could offer incentives that lead to vacating such lands by offering alternative pathways out of poverty.
- Identify areas in the humid tropics where population pressures are low but NDVI change is high as such areas are likely being deforested. Where this is taking place on poor or unsuitable soil or terrain, these practices lead to denudation and should be stopped as the land is of little agricultural use and restoration of such land is a very slow process.
- Identify areas of favourable soil and terrain where population pressure is high and degradation is in full progress. These likely are relatively resilient regions that have served as breadbaskets of Africa and require immediate attention from the development community. These are areas where fertilizer markets and land conservation measures could function and are likely to be profitable.

It is likely that further conclusions can be derived from this analysis, but such would require a modicum of ground-truthing of the findings presented here. A more detailed insight of what land degradation is happening and where may be obtained through the web-based version of this study (www.zef.de) which includes a zoom function. This allows zeroing-in on countries or parts of countries. It provides access to the respective data-bases that were employed in this study so they can be called upon for further analysis by interested parties. In a further step, it is planned to allow local experts to upload verification data and degradation details so that, over time, a monitoring tool will be created to keep track of the land in sub-Saharan Africa, on which the development of the sub-continent ultimately depends.

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Appendix 1
Pre-processing time-series AVHRR-NDVI data of African continent (1982 – 2003)

1. Data source:

The normalized differenced vegetation index (NDVI) product for a period of 22 year spanning from 1982 to 2003 was retrieved 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. The GIMMS's data are downloadable via the FPT links: ftp://ftp.glcf.umiacs.umd.edu/glcf/GIMMS/Regional/Albers/Africa/. The downloaded data are signed 16-bit integer files, TIF format in Albers Equal Area Projection.

2. Processing steps:

1) Regional masking and boundary clipping:

We used ERDAS IMAGINE 8.3 to convert the TIF files (16-bit integer) to IMG files, then converted the Albers Equal Area Projection to Geographic Projection (Long/Lat WGS 1984).

The spatial coverage of downloaded data still covers a part of the Middle East. This non-African part was first masked, and then eliminated from the dataset.

2) Pixel-based masking and fixing errors:

We conducted pixel-based masking and fixing of errors for original NDVI values according to the GIMMS guide (http://glcf.umiacs.umd.edu/data/guide/technical/GIMMSdocumentation_NDVIg_8km_rev4.pdf, pp. 8-9). The signed 16-bit integer files above are referred to as the "raw" data.

In the "raw" data, pixels with a value of -10000 were converted to -0.1 (water), and pixels with a value of -5000 were masked (null data). Raw pixels of -2000 are considered as missing data, thus also masked as null areas.

To evaluate the quality of the raw data, FLAG value of a pixel was calculated as: FLAG = raw - floor(raw/10)*10. The meaning of the FLAG index is as follows: FLAG = 6 (missing data), FLAG = 5 (NDVI retrieved from average seasonal profile, possibly snow), FLAG = 4 (NDVI retrieved from average seasonal profile), FLAG = 3 (NDVI retrieved from spline interpolation, possibly snow), FLAG = 2 (NDVI retrieved from spline interpolation), FLAG = 1 (good value, possibly snow), FLAG = 0 (good value). Hence, pixels with FLAG > 1 were also masked as null data.

Lastly, we convert all remaining "raw" data to the standard NDVI (ranging from -1 to 1) using the following formula: NDVI = fix (raw/10000)

3. Description of final products:

1) Meta data:
   Geographic projection (long/lat)
   Datum: WGS 1984
   Grid header:

ncols	953
nrows	997
xllcorner	-17.676018
yllcorner	-35.004546
cellsize	0.072727272727273 (geographic degree, or equal to 8 km)
NODATA_value	-9999

2) Temporal resolution: monthly (average of two archives a month)

3) Exported format: standard ArcInfo ASCII file (*.asc)

Appendix 2
Pixel-based test of hypothesis concerning correlation coefficient

1. Theory

The correlation between X and Y can be measured by the Pearson's coefficient R_{xy}

$$R_{xy} = \frac{\sum (X_i - \overline{\overline{X}})(Y_i - \overline{Y})}{\sqrt{\sum (X_i - \overline{X})^2 \sum (Y_i - \overline{Y})^2}}$$

Suppose we want to test the hypothesis that the correlation of X and Y (R_{xy}) is zero:

$$\mathbf{H_0: R_{xy} = 0}$$

We can use Fisher's transformation from R_{xy} to Z value that obeys normal distribution:

$$Z = \frac{1}{2}\ln\left(\frac{1+R_{xy}}{1-R_{xy}}\right)$$

The standard error of Z can be approximated to:

$$SE(Z) = \frac{1}{\sqrt{n-3}}$$

It follows that the test of hypothesis H_0 is the ratio

$$t_0 = Z / SE(Z)$$

which has a t-distribution with $df = n$-2. Suppose $t_{\alpha,df}$ is the theoretical ration (obeying t-distribution) at a confident level 1-α and the degree of freedom df, we can reject or accept hypothesis H_0 by comparing t_0 and $t_{\alpha,df}$:

- If $|t_0| \geq t_{\alpha,df}$: hypothesis H_0 is rejected. This means the correlation coefficient is significantly different from zero.
- If $|t_0| < t_{\alpha,df}$: hypothesis H_0 is accepted. This means the correlation coefficient is not significantly different from zero.

2. Pixel-based application for inter-annual NDVI and rainfall data:

Let: X_i is the mean annual precipitation (MAP), i = 1982 to 2002
Y_i is mean annual NDVI, i = 1982 to 2002
df = 21- 2 = 19

For each pixel:

- Calculating Z, $SE(Z)$ and the ratio $t_0 = Z / SE(Z)$
- If $|t_0| \geq t_{0.25,19} = 0.687$ then the calculated R_{xy} is significantly different from zero at the confident level of 75%.
- If $|t_0| \geq t_{0.1,19} = 1.328$ than the calculated R_{xy} is significantly different from zero at the confident level of 90%.
- If $|t_0| \geq t_{0.05,19} = 1.729$ then the calculated R_{xy} is significantly different from zero at the confident level of 95%.

This computation was done using matrix algebra in Spatial Analyst module (an extension of ArcView GIS 3.2).

Appendix 3
Pixel-based test of hypothesis concerning slope coefficient in simple linear repression

1. Theory

Assuming *X* and *Y* have a stochastically linear relationship:

$$Y = AX + B + \varepsilon$$

where: *A*- slope   *B*- intercept ε – random error/disturbance

We thus define:

$$S_{xx} = \sum (X_i - \overline{X})^2$$

$$S_{yy} = \sum (Y_i - \overline{Y})^2$$

$$S_{xy} = \sum (X_i - \overline{X})(Y_i - \overline{Y})$$

Hence, the least square estimator for slope *A* and intercept *B* are:

slope: $A_{cal} = \dfrac{S_{xy}}{S_{xx}}$ and intercept $B = \overline{Y} - A_{cal}\overline{X}$

The coefficient of determination is given by:

$$R^2 = \frac{S_{xy}^2}{S_{xx}S_{yy}}$$

The residual sum of squares is given by:

$$RSS = S_{yy}(1 - R^2)$$

Suppose we want to test the hypothesis that the true value of *A* is zero:

$$\boldsymbol{H_0: A = 0}$$

It follows that the test for significant of *A* is the ratio:

$$t_0 = \frac{A_{cal}}{SE(a)}$$

where *SE*(*A*) is the standard error of the slope coefficient:

$$SE(A) = \sqrt{Var(A)} = \sqrt{Var(\varepsilon)/S_{xx}}$$

The variance of error *Var(ε)* can be unbiasedly estimated by:

$$Var(\varepsilon) = \frac{RSS}{n-2} = \frac{S_{yy} - A_{cal}S_{xy}}{n-2}$$

Thus, we have: $SE(A) = \sqrt{Var(\varepsilon)/S_{xx}} = \sqrt{\dfrac{S_{yy} - A_{cal}S_{xy}}{(n-2)S_{xx}}}$

Suppose $t_{\alpha,df}$ is the theoretical ratio (obeying t-distribution) at a confidence level 1-α and a degree of freedom *df* (known from *t*-table), we can reject or accept the hypothesis H_0 by comparing t_0 and $t_{\alpha,df}$:

- If $|t_0| \geq t_{\alpha,df}$: The hypothesis H_0 is rejected. This means the calculated slope coefficient is significantly different from zero.
- If $|t_0| < t_{\alpha,df}$: The hypothesis H_0 is accepted. This means the calculated slope coefficient is not significantly different from zero.

2. Pixel-based application for inter-annual NDVI data:

Let: X_i is considered year, i = 1982 to 2003
Y_i is mean annual NDVI, i = 1982 to 2003
df = 22-2 = 20

For each pixel:

- Calculating A_{cal}, $SE(A)$ and the ratio $t_0 = Z / SE(Z)$
- If $|t_0| \geq t_{0.25,20} = 0.687$ then the calculated A_{cal} is significantly different from zero at the confident level of 75%.
- If $|t_0| \geq t_{0.1,20} = 1.325$) then the calculated A_{cal} is significantly different from zero at the confident level of 90%.
- If $|t_0| \geq t_{0.05,20} = 1.725$ then the calculated A_{cal} is significantly different from zero at the confident level of 95%.

This computation was done using matrix algebra in Spatial Analyst module (an extension of ArcView GIS 3.2).

Appendix 4
Sources of data used for the study

Data	*Hosting organization*	*Downloadable link*
NOAA-AVHRR NDVI (GIMMS) (8km × 8km)	Global Land Cover Facility (GLCF) at the University of Maryland (http://glcf.umiacs.umd.edu/data/gimms/)	ftp://ftp.glcf.umiacs.umd.edu/glcf/GIMMS/Regional/Albers/Africa/
Gridded climate of the world CRU TS 2.1 (0.5° × 0.5°)	Climate Research Unit (CRU) at the University of East Anglia (http://www.cru.uea.ac.uk/)	http://www.cru.uea.ac.uk/cru/data/hrg/cru_ts_2.10/
Gridded population of the world, version 3 (GPWv3)	Center for International Earth Science Information Network (CIESIN) at Columbia University (http://www.ciesin.org/)	http://sedac.ciesin.columbia.edu/gpw/continent.jsp?region=Africa
Global land cover GLC2000 (1km × 1km)	Global Vegetation Monitoring (GVM) Unit of the European Commission's Joint Research Centre (JRC) (http://www-gvm.jrc.it/glc2000/)	http://www-gvm.jrc.it/glc2000/ProductGLC2000.htm
Global digital elevation SRTM (1km × 1km)	Global Land Cover Facility (GLCF) at the University of Maryland (http://glcf.umiacs.umd.edu/data/srtm/)	ftp://ftp.glcf.umiacs.umd.edu/glcf/SRTM/GTOPO/
Soil constraints from Global Agro-ecological Assessment for Agriculture by IIASA-FAO (0.5° × 0.5°, or 5 arc-minute × 5 arc-minute)	The International Institute for Applied Systems Analysis (IIASA) and the Food and Agriculture Organization (FAO) of the United Nations (http://www.iiasa.ac.at/Research/LUC/SAEZ/index.html)	Soil depth constraints: http://www.iiasa.ac.at/Research/LUC/SAEZ/plates/zip/plate21.zip Soil fertility constraints: http://www.iiasa.ac.at/Research/LUC/SAEZ/plates/zip/plate22.zip Soil drainage constraints: http://www.iiasa.ac.at/Research/LUC/SAEZ/plates/zip/plate23.zip Soil texture constraints: http://www.iiasa.ac.at/Research/LUC/SAEZ/plates/zip/plate24.zip Soil chemical constraints: http://www.iiasa.ac.at/Research/LUC/SAEZ/plates/zip/plate25.zip Soil constraints combined: http://www.iiasa.ac.at/Research/LUC/SAEZ/plates/zip/plate27.zip