

# A conceptual model for assessing rainfall and vegetation trends in sub-Saharan Africa from satellite data

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**ABSTRACT:** Policymakers, governments and aid agencies require operational environmental monitoring in support of evidence-based policy-making and resource deployment in crisis situations. For Africa, this is only feasible at sub-continental scale with a large network of automated meteorological stations, a large number of highly coordinated field observers or with satellite remote sensing. The challenge with satellite data lies in the derivation of meaningful environmental indicators. This article describes a conceptual framework for understanding satellite-derived indicators of rainfall and vegetation greenness trends over Africa. It attributes observed vegetation changes to climatic (i.e. rainfall linked) and non-climatic drivers. A decade of annual rainfall and vegetation data over sub-Saharan Africa was analysed using satellite-based rainfall estimates [Famine Early Warning System Rainfall Estimation 2.0 (FEWSNET RFE 2.0)] from National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Centre and the Normalized Difference Vegetation Index (NDVI) obtained from the Satellite Pour l'Observation de la Terre Vegetation (SPOT-VGT) sensor. Rainfall and vegetation greenness trends were analysed for 759 administrative regions of sub-Saharan Africa to identify those regions that have experienced a negative, positive or stable rainfall/vegetation trend over the period 2001–2010. The character of the relationship between the annual rainfall and max NDVI trends were examined to identify areas where the changes in greenness could be attributed to climatic (rainfall) and non-climatic (human land use or ecological disturbance) changes. Regions where increasing rainfall was associated with vegetation greening were found in West Africa, Central African Republic, West Cameroon and northeastern part of South Africa, whereas areas with evidence of 'climatic vegetation degradation' were located in Southern Madagascar, Nigeria, Kenya and the Garden Route region of South Africa.

**KEY WORDS** land resources; climate change; food security; international development; environmental indicators

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## 1. Introduction

Africa has been recognized as one of the continents that is both worst affected by, and most vulnerable to, climate variability and change (IPCC, 2007). Changes in the distribution and magnitude of extreme rainfall events observed in many parts of the African continent are associated with both climate change and climate variability (Williams *et al.*, 2010), which can vary from one region to another (van de Giesen *et al.*, 2010). Extreme hydrological events such as droughts and floods are expected to increase in intensity under climate change scenarios, causing both environmental and socio-economic problems (Webersik and Wilson, 2009; IPCC, 2012). Desertification, desert encroachment and an alteration of hydrological regimes have already been observed in several African ecosystems and regions (IPCC, 2007; Descroix *et al.*, 2009;

Odjugo, 2010). A shortage of water can have a damaging impact on vegetation condition, agricultural production and livelihoods, as many African countries rely on low productivity rain-fed agriculture (Below *et al.*, 2007; Assan *et al.*, 2009). Semi-arid and arid areas concentrated in sub-Saharan Africa are particularly prone to extreme rainfall variability and water shortages. The majority of people in sub-Saharan countries (~85%) live in rural areas and are engaged in agricultural activities; thus farming is a principal source of their livelihoods (The World Bank, 2009). Barrios *et al.* (2010) provide evidence that long-term trends in rainfall have affected economic growth rates in sub-Saharan Africa in the past. Recently, long-term drying trends were observed in several African regions, for example, in Nigeria (Odjugo, 2010), the western Sahel (Ali and Lebel, 2009; Lebel and Ali, 2009), tropical North Africa (Ting *et al.*, 2009; Kawase *et al.*, 2010; Misra, 2010) and in the eastern part of southern tropical Africa (Yin and Gruber, 2010). In contrast, a study by Capecci *et al.* (2008) demonstrated that an increase in rainfall in West Africa between 1986 and 2000 had a positive effect

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on crop production, particularly on the production of millet. The 're-greening' of the Sahel since the mid-eighties that followed the great drought of the seventies was also attributed to rainfall increase (Herrmann *et al.*, 2005).

Climate change projections for Africa reported in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Christensen *et al.*, 2007) showed anticipated future decreasing rainfall trends in North, South and West Africa. In contrast, many climate models predict an increase in annual rainfall in East Africa. The largest uncertainty is how rainfall patterns will evolve in the Sahel and along the Guinean Coast. According to Christensen *et al.* (2007) the interannual rainfall variability is likely to become more pronounced leading to more intense and extreme rainfall events. Interannual rainfall variability in Africa follows a pattern that is strongly linked to the El-Niño-Southern Oscillation (ENSO). Typically during an El Niño event rainfall increases in the north and northeast and decreases in the southeast of Africa (Ropelewski and Halpert, 1987; Obasi, 2005). It is important to monitor rainfall patterns at various spatial and temporal scales, and to understand the consequences of rainfall dynamics on vegetation cover, land condition and on human populations, which are strongly dependent on natural resources, in order to detect decadal-scale oscillations and other climate fluctuations as well as longer-term impacts of climate change.

In this context, the African Monitoring of the Environment for Sustainable Development (AMESD) programme, a joint initiative of the European Commission and the African Union Commission, has extended the operational use of Earth Observation (EO) technologies and data to environmental and climate monitoring applications in Africa. The Natural Resource Monitoring in Africa (NARMA) Core Information Service of the EU GEOLAND-2 project (<http://www.gmes-geoland.info/>) has provided technical support to AMESD to develop an environmental monitoring capacity over African countries to satisfy the information needs of European Commission services and for regional and continental partner organizations in African countries. In particular, GEOLAND-2 NARMA has supplied dedicated systems [a network of low-cost and easy to use Environmental Stations (eStations)] to many African organizations for the acquisition and processing of EO data (Clerici *et al.*, 2013). The eStations periodically receive updated EO data products, including rainfall estimations (RFEs) from National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Centre processed for the Famine Early Warning System (FEWSNET) operated by the United States Agency for International Development (USAID) and the Normalized Difference Vegetation Index (NDVI) obtained from the Satellite Pour l'Observation de la Terre (SPOT) Vegetation (VGT) sensor aboard the SPOT 4 and SPOT 5 satellite platforms. The NDVI dataset is now provided by the Proba-V mission and can in future be continued through the ESA Sentinel 3 mission.

Here, we present an analysis of interannual rainfall and maximum (max) NDVI trends at national and sub-national

scale in sub-Saharan Africa. First, temporal trends are analysed at the pixel scale to identify geographic areas with decreasing, increasing or stable rainfall and vegetation greenness over the observation period from 2001 to 2010. The duration of the study period was restricted by RFE 2.0 data availability. Second, a conceptual framework for the attribution of NDVI trends to rainfall trends and other factors is presented. Such other factors are thought to be mainly human land use change, herbivory and changes in other ecological disturbance regimes such as fire. The analysis identifies areas that are subject to climatic and non-climatic changes and can help the interpretation of the vegetation temporal dynamics.

## 2. Materials and methods

### 2.1. Rainfall data

The RFE data is available since 1995 from the Africa Data Dissemination Service at <http://earlywarning.usgs.gov/fews/>. Early rainfall estimates (RFE 1.0) are available for the period from 1995 to 2000 and were derived from a combination of Meteosat 5 (satellite infrared data) and daily rain gauge data extracted from the WMO's Global Telecommunication System (GTS) data. In 2001, the RFE 1.0 was replaced by the enhanced algorithm RFE 2.0 (NOAA CPC, 2001), which additionally incorporated the two new Special Sensor Microwave/Imager (SSM/I) instruments on board the Defense Meteorological Satellite Program (DMSP) satellites and the Advanced Microwave Sounding Unit (AMSU). The RFE data showed a relatively good agreement with ground-based RFEs in several locations in sub-Saharan Africa. Symeonakis *et al.* (2009) compared two different precipitation estimation techniques based on RFE 1.0 with a dense rain-gauge network and concluded that the satellite-based precipitation estimates of FEWSNET and ground-based estimates yielded similar results over South Africa, especially in locations with precipitation around 14 mm per three decades of March 1996 (bias = 0.03 mm and  $r^2 = 0.6$ ). The best agreement was observed in southern and western Africa and Madagascar. Symeonakis *et al.* (2009) also found that over large areas with inadequate rain gauge networks such as the Sahel, satellite RFEs were performing similarly to rain gauge data. Maidment *et al.* (2013) evaluated three satellite-based rainfall products, the RFE2, GPCP-1DD and TAMSAT products, and two model re-analysis datasets (the ERA-40 and ERA-Interim) over Uganda from 2001 to 2005. The RFE 2.0 data had the highest  $R^2$  (0.74) of all gridded datasets, when compared with interpolated meteorological station data, but the other satellite data products had only marginally lower  $R^2$ . The RFE 2 dataset was chosen for our study because of its high quality and its high spatial resolution of 8 km, which makes it relevant to the spatial patterns of vegetation change. In contrast, GPCP and other products have a spatial resolution of 1° or 2.5°. At that coarser resolution, there would be too much vegetation heterogeneity within each grid cell to draw meaningful conclusions. The decadal RFE

data (at 0.25° spatial resolution) estimated rainfall particularly well for Zimbabwe and Ethiopia ( $r^2 = 0.7$ ). The RFE 1.0 product performed better than RFE 2.0 over Ethiopia, however RFE 2.0 was slightly better than RFE 1.0 over Zimbabwe (Dinku *et al.*, 2008). A study by Beyene and Meissner (2010) also showed a good correlation between monthly RFE 1.0 and RFE 2.0 data (January to December 1996–2006) and weather station rainfall records in Ethiopia ( $r^2 > 0.5$  and 0.75 depending on the month).

The RFE data is accessible as 10-day composites, which are gridded at 8 km spatial resolution – the highest spatial resolution rainfall data currently available from satellite at sub-continental scale. As the RFE algorithm was changed in 2001, and archived data could not be reprocessed using the new enhanced algorithm, the statistical analyses for our study were performed only for the period 2001–2010. This restriction limits the generalization of any conclusions drawn from the data, and particularly makes it impossible to assess climate change impacts because climate by definition describes longer-term weather patterns. It is, however, possible to infer interannual to decadal impacts of rainfall trends and other factors that change vegetation greenness. Rather than climate change, such trends are likely caused by decadal oscillations, and are influenced by the frequency and intensity of El Niño events during the observation period. Monthly rainfall was calculated at the pixel-scale from the RFE 2.0, 10-day composites, and then aggregated into a total annual rainfall in mm for each calendar year.

## 2.2. Normalized Difference Vegetation Index

NDVI was obtained from the SPOT-VGT sensor aboard the SPOT 4 and SPOT 5 satellite platforms at 1 km spatial resolution through the VGT4Africa project. The time series of NDVI data is available as 10-day max NDVI composites (S10) from April 1998 to the present. This dataset is available to many African organizations in near-real-time from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)'s Broadcast System. The retrieval of EO data from the EUMETSAT receiving station, and the computation of the environmental indicators is automatically performed by the so-called eStation, developed by the Joint Research Centre of the European Commission (Clerici *et al.*, 2013). The eStation is a comprehensive remote sensing system distributed to 47 national centres in all sub-Saharan African countries, in the framework of GEOLAND-2 NARMA (Combal *et al.*, 2010).

In this study, the maximum annual NDVI was calculated from the 10-day composites for the period 2001–2010; for the same duration as the RFE 2.0 dataset and a filtering was applied to the time series in order to remove the residual noise. Annual max NDVI was chosen because the highest NDVI value is least affected by atmospheric conditions. Any atmospheric haze or aerosols in the atmospheric column will have the effect of reducing the NDVI value. The max NDVI can thus be considered pure enough to indicate the state of the vegetation without atmospheric

influences. This study covers the complete sub-Saharan Africa and includes many different biomes from semi-arid savannah areas (where the time-integrated NDVI is a better indicator of vegetation productivity) to equatorial rainforest of the Congo Basin (where the time-integrated NDVI can be contaminated by atmospheric conditions with high cloud-cover and frequent atmospheric haze).

## 2.3. Standardization of the rainfall and NDVI time series and trend analysis

The annual cumulative rainfall and max NDVI were normalized and converted to z-scores for each year and for each pixel by subtracting a decadal mean normalized by the temporal standard deviation for the same period:

$$z_{\text{NDVI}} = \frac{\text{NDVI}_i - \frac{\sum \text{NDVI}_i}{n}}{\text{sd}_{\text{NDVI}}} \quad (1)$$

$$z_{\text{RFE}} = \frac{\text{RFE}_i - \frac{\sum \text{RFE}_i}{n}}{\text{sd}_{\text{RFE}}} \quad (2)$$

where,  $\text{NDVI}_i$  (or  $\text{RFE}_i$ ) is the annual max NDVI (or cumulative rainfall, RFE) of a pixel over  $n$  years.

The normalized datasets all have a mean of 0 and a standard deviation of 1. This approach provides a scale-independent way of jointly analysing rainfall and vegetation greenness (NDVI). Negative values indicate a rainfall deficit or decrease in vegetation greenness, while positive values define a rainfall increase or greening of vegetation.

A linear regression was carried out to identify temporal trends in rainfall (mm over 10 years) and in normalized  $z$  values of annual rainfall and max NDVI at the pixel scale. A  $t$ -test was applied to test whether the slope of the trend line was statistically significant. The type I error was controlled at <10%, and pixels with  $p > 0.1$  were interpreted as showing no significant trend over time.

## 2.4. Conceptual model for attribution of vegetation greenness trends to rainfall and other factors

The spatio-temporal relationship between trends in annual max NDVI and rainfall was attributed to four categories:

1. 'Climatic greening' is defined as areas where vegetation greening coincides with increased rainfall, suggesting a likely causal link between higher rainfall and greener vegetation.
2. 'Climatic degradation' is defined as areas where vegetation greenness and rainfall are both decreasing, suggesting that low rainfall leads to reduced vegetation vigour.
3. 'Non-climatic degradation' is detected where vegetation greenness decreases despite higher rainfall, suggesting non-climatic causes such as human land use change, herbivory, fire or other factors.

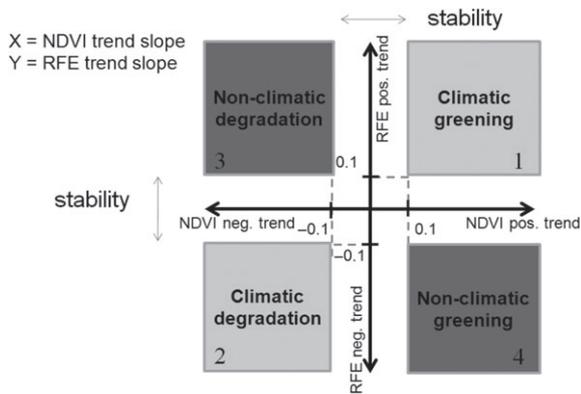


Figure 1. Conceptual model for interpreting rainfall and vegetation greenness trends and attributing the trends to climatic and non-climatic drivers.

4. 'Non-climatic greening' is detected for areas that greened up despite receiving less rainfall per year, suggesting that the greening was not caused by rainfall changes but by other factors such as artificial irrigation, reduced herbivore pressure, changed land use or other factors.

Figure 1 illustrates the concept for interpreting the joint rainfall and vegetation greenness trends.

The GlobCover map for Africa derived from data acquired by the ESA ENVISAT medium resolution imaging spectrometer (MERIS) with a 300 m spatial resolution (Arino *et al.*, 2007) was used to obtain information on the distribution of pixels of each of the four categories of the conceptual model within different land cover classes.

### 3. Results

#### 3.1. Patterns of rainfall trend

The results of the interannual rainfall trend analysis over 10 years in Figure 2 show a significant rainfall decrease over central Sahel in several regions of northern and eastern Nigeria, with the exception of coastal areas where rainfall increased and in southern Niger. A statistically significant rainfall reduction was also observed in several regions of tropical Africa – mainly in the central and southern tropical regions of the Democratic Republic of Congo, eastern Gabon, Equatorial Guinea and the central part of the Republic of Congo. Some of these regions are characterized by a large rainfall reduction of more than 20 mm over 10 years.

In contrast to the observed rainfall reduction in the central Sahel, the western Sahel (i.e. Senegal, western Guinea and southern Mauritania) experienced significantly wetter conditions, with rainfall increasing by more than 20–30 mm over the period 2001–2010. The years 2008, 2009 and 2010 were particularly wet in western Africa. Furthermore, a significantly increasing rainfall trend and high rainfall variability was observed from 2001 to 2010 in several regions in western Namibia and south-western Angola.

The increase in rainfall in East Africa, extending to the Horn of Africa (Ethiopia, Somalia, East Eritrea and Tanzania) was generally not statistically significant, except for the Mare region in western Ethiopia and the Mudug region in Somalia, where significant increases were observed.

#### 3.2. Patterns of max NDVI trend

The number of pixels with a positive trend in annual max NDVI is greater than those with a negative trend (Figure 3). The regions with a significantly positive NDVI trend are located mainly in western and central Africa, the western part of the Sahel region and across the central part of southern Africa. In many of these locations the vegetation condition showed highly significant increases in NDVI by  $>0.01$ . In general, the vegetation condition remained quite stable or showed a small increase in NDVI values ( $<0.005$  and  $<0.01$ ) across central Africa, over the Congo Basin, and the southern part of the Sahel region (Figure 3).

NDVI decreased significantly in eastern Africa (Ethiopia, Somalia, Kenya and Tanzania), southern Madagascar, in the central part of the Sahel region as well as in the southern part of the Eastern Cape region of South Africa.

#### 3.3. A concept for attribution of vegetation greenness trends to drivers of change

Figure 4 presents the result of the simple conceptual model for interpreting rainfall and vegetation greenness trends and attributing the trends to climatic and non-climatic drivers illustrated in Figure 1. Figure 4 presents only areas characterized by a statistically significant relationship ( $p < 0.1$ ) between annual rainfall and max NDVI. Regions showing climate-driven greening up were found in West Africa, western Sahel, Central African Republic, West Cameroon and the northeastern part of South Africa. The analysis of the GlobCover map showed that a climate-driven greening trend occurred predominantly in locations covered by a mosaic of cropland, grassland and vegetation (shrubland/forest) (29% of the total greening area), herbaceous and sparse vegetation (16%), closed and open shrubland (16%) and cultivated and managed land (4%). Of the total greening trend area, 27% was closed/open forest, of which around 20% was broadleaved deciduous forest and 7% was evergreen forest (mainly western Gabon and some northeastern parts of the Congo Basin). In some areas of northern and southeastern Nigeria, western Cameroon, central Uganda and central Madagascar, vegetation greenness increased between 2001 and 2010 despite a significant rainfall reduction, indicating non-climatic greening according to the simple attribution model.

The analysis of the GlobCover map showed that 8% of the total non-climatic greened-up area was on cultivated and managed land (including post-flooded or irrigated croplands, 0.3%), 15% mosaic of cropland, grassland and vegetation (shrubland/forest) and 6% closed/open shrubland, 4% forest regularly flooded and 4% herbaceous and sparse vegetation. 'Non-climatic greening' was also

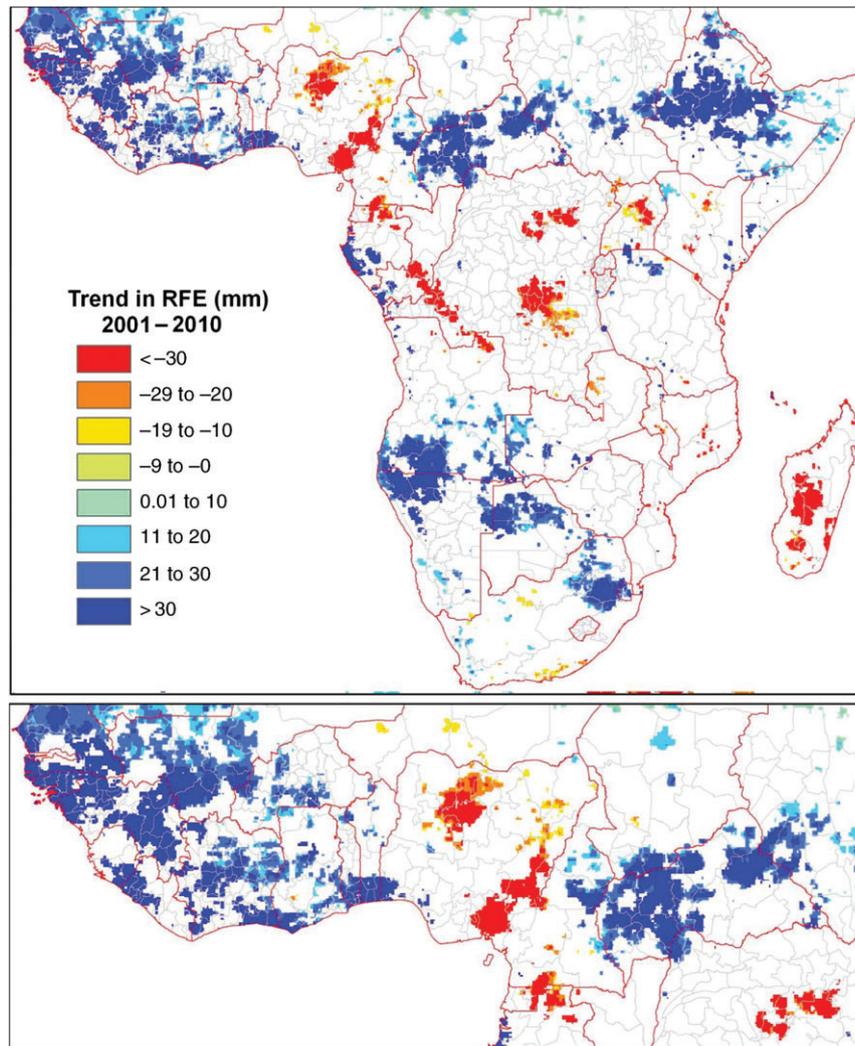


Figure 2. Statistically significant ( $p < 0.1$ ) trends in annual rainfall amount (mm) from 2001 to 2010 at the pixel scale derived from FEWSNET RFE 2.0 data. Red lines indicate administrative boundaries level-1 (country) and grey lines level-2 and level-3 (Sudan and Democratic Republic of Congo). A vector layer of administrative divisions was provided by Food and Agriculture Organization of the United Nations (FAO) (<http://www.fao.org>).

observed in tropical Africa over a dense humid forest in the Democratic Republic of Congo. More than 62% of the total non-climatic greening trend occurred in forest areas, of which 35% was evergreen forest (central Democratic Republic of Congo, northern Gabon and southern Cameroon) and the remaining 27% was broadleaved deciduous forest (Figure 4).

Non-climatic degradation of vegetation was detected in several locations in the Horn of Africa, Burkina Faso, the southern part of Mali and Central Cameroon. The largest area of non-climatic degradation was identified in Ethiopia, where overall degradation was found in almost 2% (more than 20 400 km<sup>2</sup>) of the country (the Tigray, Welo, Welega, Harerge and Shewa regions), whereas climatic greening has affected more than 3% (36 400 km<sup>2</sup>) of Ethiopia (mainly the Arsi, Shewa, Gojam and Welega regions). Small pockets of non-climatic degradation were also identified in many other places in sub-Saharan Africa. Of the total non-climatic degradation area, 39% was in mosaics of cropland, grassland and vegetation (shrubland/forest), 20% was herbaceous and

sparse vegetation, 12% was closed/open shrubland, and 6% cultivated and managed land. Almost 8% of the total non-climatic degradation of vegetation was located in closed/open forest (predominantly broadleaved deciduous forest).

Areas with evidence of climatic degradation of vegetation are located in southern Madagascar, Nigeria, Kenya and the southern part of South Africa. More than 38% of the total climatic degradation area was occupied by herbaceous and sparse vegetation, 21% by mosaic of cropland, grassland and vegetation (shrubland/forest), 15% by closed/shrubland, 10% by closed/open forest (mainly broadleaved deciduous forests), and 6% by cultivated and managed land.

#### 4. Discussion

##### 4.1. Rainfall patterns

A statistically significant decreasing trend in rainfall was observed in this study in several regions of the

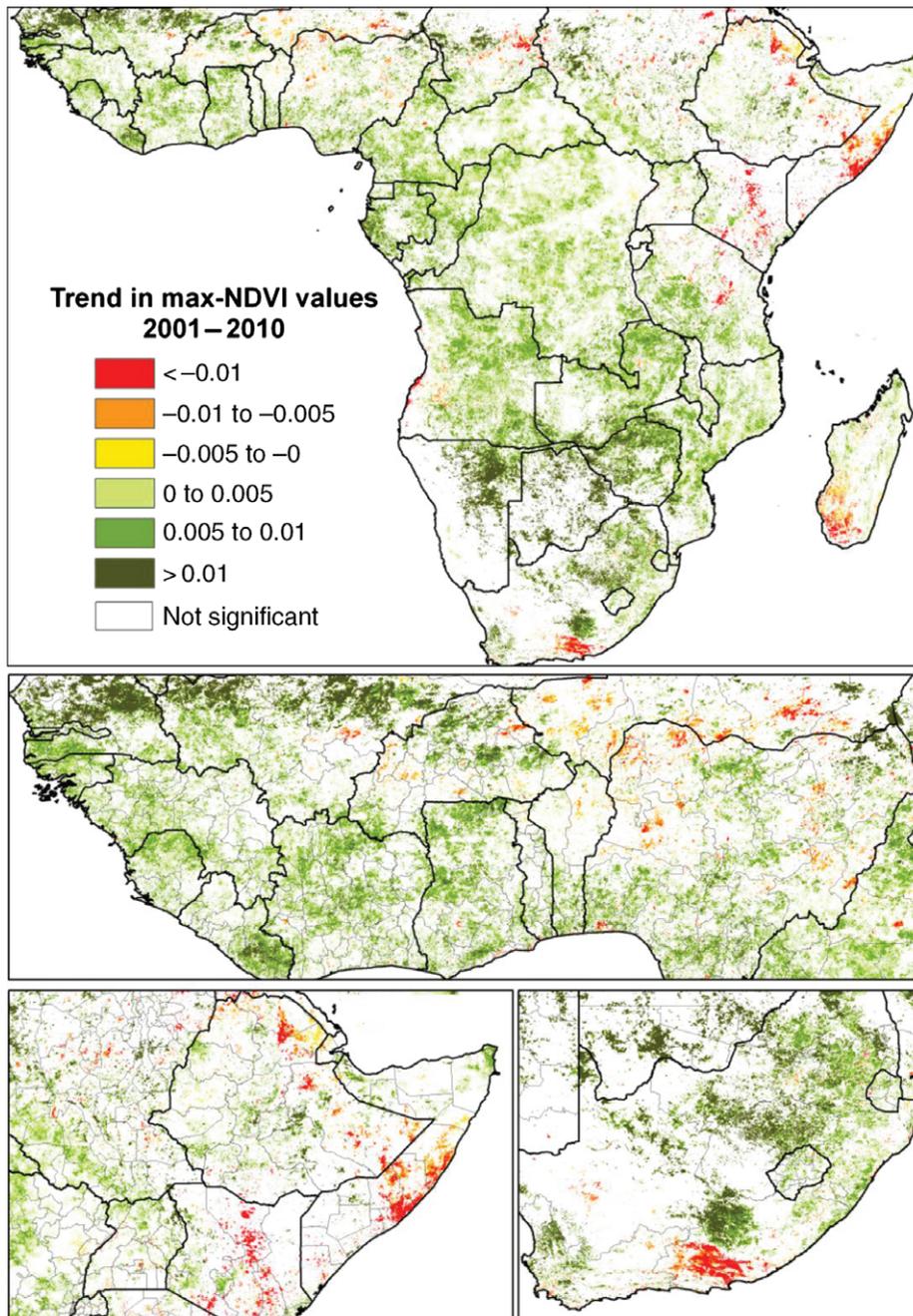


Figure 3. Statistically significant ( $p < 0.1$ ) trends in annual max NDVI values for the period 2001–2010. Black lines indicate administrative boundaries level-1 (country) and grey lines level-2 and level-3 (Sudan and DR of Congo). A vector layer of administrative divisions was provided by FAO ([www.fao.org](http://www.fao.org)).

central Sahel and Nigeria, which is coherent with findings by Odjugo (2010) from meteorological data between 1901 and 2005 and by Lebel *et al.* (2009) over the period 1940–2000. This decreasing trend appears to continue in northern Nigeria and southern Niger over the period of satellite observations presented by this study (2001–2010).

The reason for the observed rainfall increase in the western Sahel lies in the series of wet years that occurred after 2002, in contrast to the two unusually dry years at the beginning of the period of investigation. The effect of this increase in rainfall was assessed by a long-term analysis of

satellite observations, which shows a general re-greening of Sahel for the period 1982–2003 (Herrmann *et al.*, 2005). On the other hand, Lebel and Ali (2009) concluded from an analysis of a longer time period (1950–2007) that the initial 20-year wet period (1950–1969) was followed by a 40-year dry period (1970–2007) in the western Sahel. We observed that the last 3 years: 2008, 2009 and 2010 were extremely wet in western Africa. According to the UN Office for the Coordination of Humanitarian Affairs (OCHA, 2010) the year 2010 has seen the largest number of people affected by flooding with many casualties. These three subsequent unusually wet years may indicate

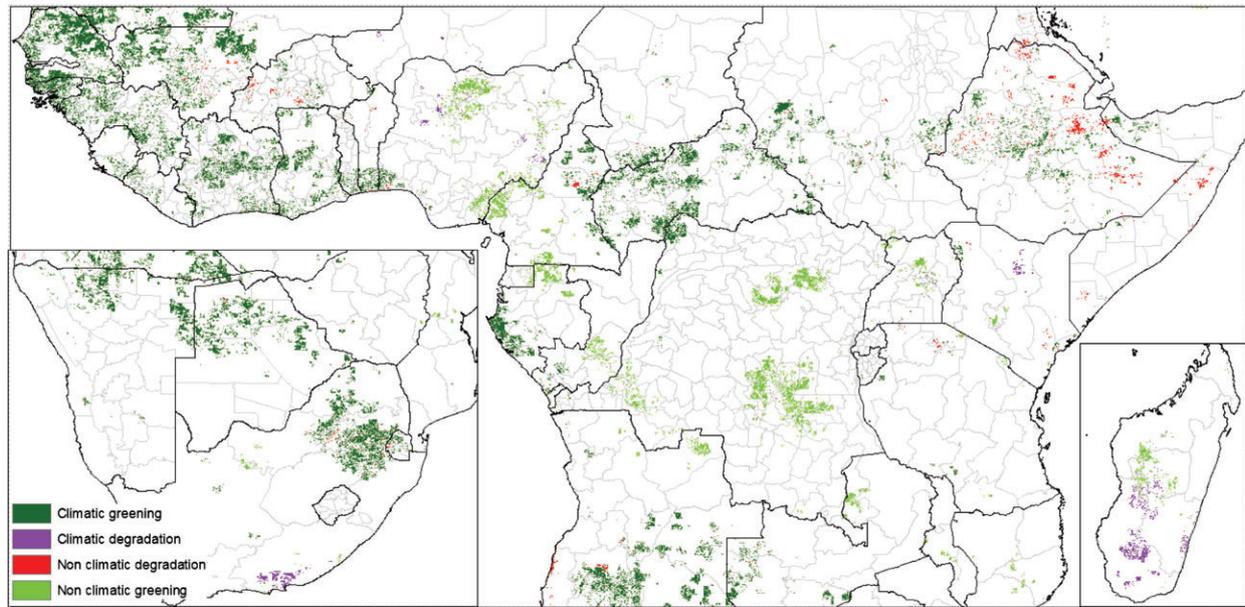


Figure 4. Distribution of areas that have experienced climatic greening (degradation) and non-climatic greening (degradation) in sub-Saharan Africa according to the concept for attribution of changes. Black lines indicate administrative boundaries level-1 (country) and grey lines level-2 and level-3 (Sudan and DR of Congo). A vector layer of administrative divisions was provided by FAO ([www.fao.org](http://www.fao.org)).

a tipping point in the rainfall regime observed by Lebel and Ali (2009), which may suggest the beginning of a longer wet period. Future rainfall scenarios, however, are rather uncertain in this region due to the complexity of the physical mechanisms responsible for Sahelian rainfall patterns (Christensen *et al.*, 2007; Giannini *et al.*, 2008).

Furthermore, Usman and Reason (2004) analysed a longer time-series (1979–2004) and showed that the most significant increases in occurrences of heavy rainfall events were observed in central Namibia and Angola in the west. Our study indicates that this trend continued from 2001 until 2010. The rainfall patterns of these areas are mainly influenced by the Atlantic SST and North Atlantic Oscillation related wave train, while the Atlantic Walker Cell and ENSO have a minor impact (Jury, 2010).

A statistically significant rainfall decrease found here for several regions of tropical Africa was also reported by Yin and Gruber (2010) who studied long-term satellite and rain gauge data (1979–2004) in tropical Africa and found a large-scale rainfall reduction in the eastern part of southern tropical Africa over part of the Congo basin starting in 1992. A long-term drying trend was also observed over the northern part of the tropics by Kawase *et al.* (2010), which was mainly caused by an increase in anthropogenic aerosols influencing both atmospheric dynamics and thermodynamic effects. A recent study by Zhou *et al.* (2014) also confirmed a decline in rainfall across the large area of central and northern Democratic Republic of Congo. A reduction in rainfall across tropical ecosystems could have a significant impact on the climatic condition at the global and regional scale considering that the Congo Basin is the second largest rainforest on earth. The rain gauge measurements used for the RFE products are not homogeneously distributed over Africa, thus the confidence level in RFE

is not stationary and depends on the considered location. There are large gaps in the coverage with rain gauges in large parts of the Democratic Republic of Congo and Angola.

#### 4.2. Vegetation patterns

The vegetation greening over the western part of the Sahel belt reported here was also observed since the mid-1980 after ‘the great Sahelian drought’ of the 1960s and 1970s (Heumann *et al.*, 2007; Fensholt and Rasmussen, 2011). By contrast, several locations in the central Sahel region (southern Niger and southeastern Chad) experienced a decreasing trend in vegetation greenness. Pricope *et al.* (2013) found a consistently declining NDVI over the period 1999–2011 in northern and eastern Ethiopia, along the Somali coast and in central Kenya, where this pattern extended into central Tanzania. A similar pattern of vegetation deterioration was identified in the East African Horn by our study and by de Jong *et al.* (2012). Here, a positive trend in vegetation greenness was also found across central parts of southern Africa, which is in accordance with Harris *et al.* (2014). A noticeable exception to this positive trend is the southern part of the Eastern Cape region of South Africa. This region has experienced several severe droughts over the last decades affecting the vegetation condition (Ngaka, 2012). The locations with statistically significant NDVI reduction are likely to have experienced less favourable growing conditions or disturbances like herbivory, grazing, land use change or human disturbance (Pricope *et al.*, 2013; Vrieling *et al.*, 2013).

#### 4.3. A conceptual model – link with previous studies

Regions where increasing rainfall was associated with vegetation greening are assumed to show a climate-driven

greening up trend. In these regions, the water availability is the most influential factor driving vegetation growth. Several studies based on time series of satellite data have confirmed a climate-driven greening up effect in the Sahel belt after the 1980s (Fensholt and Rasmussen, 2011, Heumann *et al.*, 2007). Climatic greening up in West Africa and other parts of sub-Saharan Africa may have an effect on the increasing trend in the length of the growing season and may consequently increase agricultural productivity (Vrieling *et al.*, 2013). Climatic greening was predominantly observed across areas covered by a mosaic of cropland, grassland, cultivated and managed land, where vegetation responds to both natural environmental variability and to anthropogenic changes.

The non-climatic greening, where vegetation greenness improved from 2001 to 2010 despite a significant rainfall reduction may be associated with new irrigation practices, better agricultural land use management, and changes in the types of dominant crops, a reduction in vegetation disturbance by grazers, herbivores, fire and people or similar causes. According to the results presented here, almost 27% of non-climatic greening occurred on agricultural land. A recent study by Boschetti *et al.* (2013) showed that in some places of the Sahel region the greening up trend is associated with the expansion of irrigation, and vegetation reductions are caused by unsustainable pastoral and land use practices that lead to natural resource over-exploitation. Interestingly, more than 62% of the total non-climatic greening trend occurred in forests, half of which was evergreen forest located in central Democratic Republic of Congo, northern Gabon and southern Cameroon. This may be explained by the fact that a reduction in the annual rainfall sum does not limit the vegetation growth in these areas due to the generally very wet conditions. However, a recent study by Zhou *et al.* (2014) also presented evidence for a widespread decline in forest greenness particularly in the northern Congo Basin over the decade 2000–2012. The authors explained that this decline of vegetation greenness is related to a decrease in rainfall and increase in photosynthetically active radiation and land surface temperature. Tropical ecosystems are particularly sensitive to prolonged water stress conditions, which may in the long term lead to a reduction in net primary productivity, consequently leading to a displacement of vegetation types in the long term (Gritti *et al.*, 2010). Our results show a rainfall decrease in northern and central parts of the Congo Basin but no decrease in vegetation greenness. The condition of evergreen vegetation across this area remained mainly constant or showed a small but statistically significant increase in NDVI values by  $<0.005$  and  $<0.01$  in contrast to negative rainfall trends of  $<-30$  mm over 10 years. This discrepancy in vegetation patterns may be explained by the fact that Zhou *et al.* (2014) used the Enhanced Vegetation Index (EVI) in their study, which is more sensitive to dense forest than other vegetation indices such as the NDVI used here. EVI has been used widely in recent studies of tropical rainforest in the Amazon (Samanta *et al.*, 2012).

Regions where rainfall has increased from 2001 to 2010 but vegetation greenness decreased nonetheless were classified as non-climatic degradation of vegetation. Possible causes for the reduced vegetation greenness include human land use change, increased livestock density on grazing land, changes to the fire regime, increasing herbivore densities and similar pressures. Of the total non-climatic degradation areas reported here, around 45% occurred on cultivated land and in mosaics of cropland, grassland and natural vegetation. Such regions were detected in the Horn of Africa, Burkina Faso, the southern part of Mali and Central Cameroon. These regions generally experience a strong human population growth. In Mali, near the border with Burkina Faso, for example, a significant population increase by 35–45% over the last decade has resulted in a reduction of herbaceous and shrub vegetation being replaced by bare soil (Boschetti *et al.*, 2013). Similarly, the highly populated areas along the Okavango Delta in northern Botswana and along the Niger River in western Mali as well as areas close to the big cities experienced non-climatic degradation, which were also confirmed by other studies (Pricope *et al.*, 2013; Harris *et al.*, 2014). Long-term studies by Mougin *et al.* (2009) confirmed a decrease in natural vegetation and an increase in agricultural areas in Mali. Our study shows that the largest area of non-climatic degradation was identified in Ethiopia and overall in the Horn of Africa. The Horn of Africa was recognized as one of the most food insecure regions with increasing population since the early 1990s (Pricope *et al.*, 2013).

Almost 8% of the total non-climatic degradation of vegetation was located in closed/open forest (predominantly broadleaved deciduous forest), which may indicate an ongoing deforestation process. High rates of deforestation in Africa's rainforests in the Congo Basin and Madagascar were reported between 1990 and 2010 by Mayaux *et al.* (2014). This pattern was not observed from the NDVI study here, probably because of the saturation of NDVI in dense forest (Atkinson *et al.*, 2011). Regions where decreasing rainfall was associated with declining vegetation greenness are assumed to show climatic degradation. Small pockets of climatic degradation were located in northern Kenya, where Pricope *et al.* (2013) identified statistically significant long-term decline in mean growing season, which may indicate general degradation of vegetation. Around 21% of climatic degradation identified in our studies occurred in mosaics of cropland, grassland and natural vegetation.

#### 4.4. Limitations of the conceptual model

The presented conceptual model for the attribution of vegetation greenness trends to rainfall changes and non-climatic factors allows the identification of four basic categories of change and the associated areas where these types of vegetation dynamics take place. This simple and intuitive concept can be used for a rapid assessment of anomalous behaviour of rainfall and NDVI trends at the

regional to continental scale. By relating the results from the conceptual model to previously published studies, this article has demonstrated its general applicability and validity in areas where rainfall is the primary factor constraining vegetation growth, as is evident from the results for the semi-arid and arid environments in sub-Saharan Africa presented here. The model is less reliable in the wet tropics, where radiation is usually the limiting factor to vegetation growth. In addition, the model is based on NDVI, which tends to saturate in dense forest (Atkinson *et al.*, 2011).

Interpretation of the identified typology of changes requires additional knowledge and supplementary analyses of other contributing factors such as changes in grazing pressure, irrigation, use of fertilizer, deforestation or afforestation, in particular where 'non-climatic changes' are detected. These supplementary analyses should be performed at a more local scale using higher resolution satellite data and ancillary information from field observations. Nutini *et al.* (2013), for example, use a set of Landsat images from 2000 to 2007 to produce land cover maps in a semi-arid region of Niger, where an anomalous vegetation trend was previously detected.

The conceptual model is based on trends in annual rainfall and max NDVI calculated for each calendar year. The calendar year is typically used for reporting periods; however, using the calendar year can lead to inconsistencies in the southern hemisphere where two different vegetation growing seasons are the norm. The synthesis of the vegetation greenness and rainfall trends at the national and sub-national scale is motivated by the needs of government departments and decision makers at various levels to support implementation processes for their environmental policies. The categorized data of climatic and non-climatic changes, delivered at national and sub-national scales, can be incorporated into a Country Environmental Profile (CEP), the document that provides necessary information used for integration of environmental concerns. In recent years, there has been an increasing desire to provide evidence-based policies at the same time as a much-improved availability of data from which environmental information can be derived. This information can support the implementation of environmental issues in international cooperation policy. To date, many decision makers still largely tend to use non-spatial indicators of environmental conditions and human impact.

Finally, any changes in rainfall over the study period may be due to decadal-scale climate fluctuations or longer-term climate change. The conceptual model presented here does not make any assumptions about the persistence of climatic trends, and is not suitable to detect climate change from short time-series data like the 10-year dataset analysed here. Rather it aims to identify areas that are likely affected by anthropogenic activities or rainfall changes, respectively. This information alone is thought to be of value to decision makers. Longer-term general circulation models coupled to land surface/dynamic vegetation

models have to be run to make predictions of climate change trends.

## 5. Conclusions

The purpose of this study was to present a concept for attributing vegetation greenness changes to different drivers using satellite datasets that will be growing in length over time. While the length of the dataset analysed here does not allow a detection and attribution of climate change impacts on vegetation and rainfall in Africa, the concept is nevertheless applicable to longer-term time-series in principle. As the archive of satellite data grows, such methods will eventually lead to the detection and attribution of climate change impacts. In reality, any longer-term climate signal will be confounded by the impacts of decadal-scale climate oscillations and impacts of El Niño events in the time-series. However, based on previously published studies from long-term meteorological station networks, we have identified some regions where the rainfall trends are consistent with long-term climate model predictions.

The results have shown that spatial patterns of different change processes can be detected in specific regions of Africa, which are generally consistent with independently reported literature on longer-term trends, El Niño effects and decadal-scale climate oscillations. This study confirmed that most of the vegetation in sub-Saharan Africa depends on rainfall variability, particularly in the semi-arid and arid environments; however, there are areas where degradation of vegetation condition is driven by other anthropogenic or natural factors. The concept proved to be less reliable in the wet tropics. Use of coarse resolution satellite data can be a valuable source of information leading to better understanding of the drivers of change.

The monitoring concept described here is being implemented in the European Commission, serving the needs of both European services and African institutions. This operational land monitoring concept for Africa is continued in the AMESD project and through the 'Monitoring of Environment and Security in Africa' (MESA) programme, supported by the European Development Fund and implemented by the African Union (2013–2018). MESA will improve natural resource management and sustainable development. Future satellite data provision will continue through the Sentinel satellites by the Copernicus (formerly GMES) initiative, Proba-V and other missions.

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