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Recent trends in vegetation dynamics in the African Sahel and their relationship to climate

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Abstract

Contrary to assertions of widespread irreversible desertification in the African Sahel, a recent increase in seasonal greenness over large areas of the Sahel has been observed, which has been interpreted as a recovery from the great Sahelian droughts. This research investigates temporal and spatial patterns of vegetation greenness and rainfall variability in the African Sahel and their interrelationships based on analyses of Normalized Difference Vegetation Index (NDVI) time series for the period 1982–2003 and gridded satellite rainfall estimates. While rainfall emerges as the dominant causative factor for the increase in vegetation greenness, there is evidence of another causative factor, hypothetically a human-induced change superimposed on the climate trend.

Keywords: Desertification; Greening; Sahel; Remote sensing; Time series analysis

1. Introduction

The African Sahel, a semi-arid grass- and shrubland region bordering the Sahara desert to the south, is a dynamic ecosystem that responds to fluctuations in climate and anthropogenic land use patterns. Contrary to largely anecdotal assertions of widespread irreversible 'desertification' in the Sahel (e.g. Lamprey, 1975, reprinted in 1988), recent findings based on analyses of satellite images report an increase in greenness over large areas of the Sahel since the mid-1980s, which, at a coarse scale, is well correlated with an overall increase in rainfall and has been interpreted as a recovery of the vegetation from the great Sahelian droughts in the 1970s and 1980s (Tucker and Nicholson, 1999; Eklundh and Olsson, 2003) However, the greening trend is not uniform, suggesting that factors other than rainfall may have contributed to a differential greening response, with greening taking place in some areas but not in others.

Although its actual meaning on the ground has not yet been firmly established, the observed greening trend has challenged notions of irreversible damage inflicted on the Sahelian ecosystem (Dregne, 1983; Middleton et al., 1997), revived debates about the concept of desertification, and triggered re-assessments of its nature, scale and extent, facilitated by progress in remote sensing technology as a tool for environmental monitoring and analysis. However, while studies based on long time series of satellite and ground data have confirmed the dynamic nature of the Sahelian ecosystem and its susceptibility to change, they have not resulted in a consensus on either the direction of changes or its underlying causes.

2. Background

The Sahel (Arabic for 'shore') is a transition zone between the arid Sahara in the north and the (sub-) humid tropical savannas in the south, and is marked by a steep north–south gradient in mean annual rainfall (Le Houerou, 1980). The rainfall gradient is expressed on the ground in

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a continuum of change in vegetation species and life forms from the Saharan biome with very sparse vegetation cover—thorny shrubs interspersed between annual and perennial grasses—to the Sudanian and Guinean biomes, characterized by a higher amount of ground cover, taller vegetation and a greater proportion of woody species (White, 1983). Species thin out and eventually disappear or appear gradually, but 'at no moment would you have the impression of crossing a biological frontier' (Monod, 1985, p. 204).

The climate of the Sahel is characterized by a marked seasonality with a long dry season and a short humid season in the northern hemispheric summer, which is explained by the position of the region relative to major global and regional circulation features and the seasonal variation of tropical weather patterns (Nicholson, 1995). Climatic constraints, i.e. not only scarcity but also variability and unpredictability of rainfall, which increase from south to north, are the most important controlling factors of the Sahelian ecosystem. The vegetation cycle closely responds to the seasonality in rainfall, with virtually all biomass production taking place in the humid summer months. The sharp seasonal contrasts are overlain by considerable fluctuations in rainfall at inter-annual and -decadal time scales, which make the Sahelian region the most dramatic example of climate variability that has been directly measured (Hulme, 2001). Causes for long-term rainfall fluctuations are complex and can be found in changing configurations of forcings and feedback mechanisms, which can be induced by atmospheric and ocean circulation dynamics with global-scale effects, such as the El Nino southern oscillation (ENSO) cycles (Nicholson, 2001; Nicholson and Grist, 2001), non-ENSO-related variations in sea surface temperatures (Giannini et al., 2003; Brooks, 2004), and large-scale changes in land cover and land–atmosphere interactions (Charney et al., 1975; Hulme and Kelly, 1993; Nicholson, 2000; Hulme et al., 2001; Zeng et al., 1999). Furthermore, a number of modeling studies point to possible links between Sahelian rainfall variability and anthropogenic global warming (e.g. Eltahir and Gong, 1995; Giannini et al., 2003).

Although variability in rainfall and the occurrence of droughts are seen as normal phenomena in arid and semi-arid climates (Glantz, 1987), rendering mean annual rainfall figures almost meaningless (Hulme, 2001), the droughts that affected the Sahelian region in the late 1960s through the 1980s following a series of favorable years were unprecedented in this century in their length and impact. Land degradation and famine conditions during these droughts, exacerbated by political instability and unrest, have triggered an upsurge in interest in the issues at work in the Sahel and appropriate countermeasures that might be taken, resulting in the United Nations Conference on Desertification (UNCOD) in 1977. The conference has prompted an ongoing and still unresolved debate about the causes and effects of drought, land degradation and desertification (Herrmann and Hutchinson, 2005). Two competing camps represent diametrically opposed positions in this debate: while adherents of the desertification hypothesis hold human activities responsible for a—hypothetically irreversible—decline in vegetation conditions in the Sahel, expressed as 'overuse of resources' and 'human mismanagement' (Mensching, 1990; Mainguet, 1991; Ibrahim, 1978), desertification skeptics interpret declines in vegetation condition and density as drought-induced and hence temporary phenomena, with humans playing only a minor role, if at all (Nicholson et al., 1998; Olsson et al., 2005). Mortimore and Adams (2001), Tiffen and Mortimore (2002) and Reij et al. (2005) report local-scale 'success stories' and stress the high potential of adaptation of the Sahelian population to rainfall variability in time and space. A growing archive of satellite observations has indeed shown a close coupling between vegetation greenness and rainfall variability. Tucker and Nicholson (1999) found the green vegetation boundary of the Sahel to fluctuate by up to 150 km from a wet year to a preceding dry year in response to rainfall. With such great natural fluctuations, the permanence of land degradation in the form of desertification can only be established by monitoring susceptible areas over a time scale of decades.

Ecosystem monitoring, in the Sahel and elsewhere, has been facilitated by progress in remote sensing technology and the availability of data sets at ever finer spatial, temporal and spectral resolutions. Remote sensing presents important advantages to the monitoring of vegetation dynamics and land degradation—such as the synoptic perspective it offers—however, there are limitations to this technology that also have to be taken into account. As a synergistic tool, remote sensing does not unfailingly distinguish between different vegetation types and, therefore, might hide changes in vegetation cover not associated with changes in overall greenness, such as shifts in vegetation composition. Other limitations arise from the technological and cost-induced trade-offs between different types of resolution, such that simultaneous increases of spatial, spectral and temporal resolutions, all of which can provide more precise information in different aspects of vegetation dynamics, in one system are inhibited (Cihlar, 2000).

3. Objectives and rationale

In light of the ongoing debate about the driving forces of vegetation dynamics and land degradation in the Sahel and the still insufficient distinction made between the effects of drought and 'desertification', the objectives of this research were to (1) further explore the relationship between climatic and anthropogenic causes of land degradation at a coarse resolution, (2) break down trends in precipitation and vegetation dynamics into spatial patterns and (3) identify hotspots of potentially human-induced land degradation as well as rehabilitation for further study at finer spatial resolution.

The relationship between vegetation and rainfall in semi-arid environments has received a great deal of interest, notably in the African Sahel. Most previous regional-scale studies were based on time series of remotely sensed indicators of vegetation greenness, mainly the Normalized Difference Vegetation Index (NDVI), and rainfall measurements from ground stations. Nicholson et al. (1990) found a linear relationship between rainfall and NDVI in the Sahel below a rainfall threshold of about 1000 mm/year. The correlation between the two variables was found sufficiently strong to use NDVI as a proxy for mapping rainfall variations (e.g. Tucker and Nicholson, 1999). Prince et al. (1998) used rain use efficiency, a ratio between net primary production and rainfall, to characterize vegetation response to rainfall and found an upward trend over most of the Sahel for the period 1982–1990. Significant increases in vegetation greenness, in phase with increasing rainfall, were noted by Eklundh and Olsson (2003), who studied trends in NDVI amplitude and time-integrated NDVI for the period 1982–1999. While all these studies refute claims of widespread desertification in the Sahel at a coarse resolution and indicate overall positive developments in both vegetation and rainfall since the mid-1980s, few efforts have been made to explicitly disentangle the effects of climate/rainfall and human impact on vegetation dynamics in the Sahel.

This research, building on findings of previous studies about the nature of the relationship between rainfall and vegetation greenness in the Sahel, carries the analysis of this relationship one step further to address the question of a possible 'human signal' in vegetation dynamics. It is hypothesized that, if there is any significant human signal detectable at the coarse resolution of 8 km in addition to the climate signal, it would show in the residuals after removal of the climate signal from the NDVI data set.

4. Data sets

4.1. Normalized Difference Vegetation Index

The NDVI was employed in this study as a proxy for vegetation greenness. The data is derived from measurements made by the Advanced Very High Resolution Radiometer (AVHRR) instrument on board the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite series. The NDVI, a normalized ratio of the near-infrared and red spectral reflections (NIR−red/NIR+red), is sensitive to the presence, density and condition of vegetation and is correlated with absorbed photosynthetically active radiation (PAR) and vegetation primary production. It exploits the different spectral characteristics of bare soil and green vegetation in the red and near-infrared portions of the electromagnetic spectrum, with reflectance in the red decreasing with increasing chlorophyll absorption and reflectance in the near-infrared increasing with increasing green plant biomass (Tucker, 1979; Rouse et al., 1974; Tucker et al.,1985, Myneni et al., 1995). The NDVI is the oldest remotely sensed vegetation index in use and remains, despite its shortcomings (sensitivity to soil color, atmospheric effects, illumination and observation geometry), the most widely used by the remote sensing community. The development of alternative vegetation indices—the Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988), the Modified Soil-Adjusted Vegetation Index (MSAVI) (Qi et al., 1994), the Atmospherically Resistant Vegetation Index (ARVI) (Kaufman and Tanre, 1992) and the Enhanced Vegetation Index (EVI) (Huete et al., 2002)—aimed at minimizing some of these problems, has not resulted in the creation of a consistent time series for universal application.

A monthly NDVI time series for the period 1982–2003 was taken into consideration. Data for the year 2004 were omitted from the study because of scan motor problems of the AVHRR-16, which produced bar code noise and resulted in data of poor quality (http://www.oso.noaa.gov/poesstatus/). NOAA AVHRR satellite sensors have been operational for more than two decades and offer a length of record that is unmatched. However, the AVHRR NDVI time series is afflicted with some non-negligible errors induced by the lack of on-board band calibration, atmospheric effects differing between the respective bands and variations in solar illumination and sensor view angles produced by satellite overpass time drifts (e.g. Slayback et al., 2003). Yet, the effects of satellite drift on NDVI are rather small in sparsely vegetated biomes: for the Sahel, 2% of the variance of NDVI could be explained by the solar zenith angle effect (see Pinzon et al., 2004, Table 1). The NDVI time series used here is an 8 km spatial resolution monthly maximum value composite processed by the Global Inventory Modeling and Mapping Studies (GIMMS) Group at NASA's Goddard Space Flight Center (Tucker et al., 2005), in which the above-listed biases have been minimized or eliminated. In particular, the GIMMS NDVI has been corrected for residual sensor degradation and sensor intercalibration differences, effects of changing solar zenith and viewing angles, volcanic aerosols, atmospheric water vapor and cloud cover using nonlinear empirical mode decomposition methods (Pinzon et al., 2004; Huang et al., 1998) and maximum value compositing to minimize cloud contamination (Holben, 1986). As a result, the GIMMS NDVI data set used in this study is relatively consistent over time and shows a high level of precision for semi-arid and arid areas. In comparison with other NDVI data sets—Pathfinder Land (PAL) and Global Vegetation Index (GVI)—and previous versions produced by the GIMMS group, the new GIMMS NDVI has been found to be of superior quality (Brown et al., 2003).

4.2. GPCP and TRMM gridded precipitation estimates

Rainfall measurements from rain gauge stations are conventionally considered the most accurate and reliable source of rainfall data; however, this is only true for point measurements or areas with a sufficiently dense network of rain gauges. Throughout most of the Sahel, rain gauges are sparse and of varying reliability, and measurements not always easily available (Adeyewa and Nakamura, 2003; Nicholson et al., 2003a). As a proxy for rainfall, gridded satellite precipitation estimates were used in this study, which combine satellite observations from different sources and ground measurements where available into area-averaged precipitation fields. The principles behind these merged data sets, which exploit the strengths of each of the data sources to improve the overall quality of precipitation estimation, and the combination methodology are explained in more detail in Xie and Arkin (1995, 1997), Ardanuy and Arkin (1989) and Adler et al. (2003). The GPCP Version2 combined precipitation data set produced monthly by the Global Precipitation Climatology Project (GPCP) at 2.5° spatial resolution was used for the period 1982–2003. In addition, the merged product 3B43 from the Tropical Rainfall Measuring Mission (TRMM) available at 1° spatial resolution for the shorter period 1998–2003 served as a means of validation of the GPCP-based results. The GPCP product integrates, in weighted averages, infrared observations from the Geostationary Operational Environmental Satellite (GOES), Geosynchronous Meteorological Satellite (GMS) and Meteosat with microwave estimates from the Special Sensor Microwave Imager (SSM/I) and rain gauge data (Adler et al., 2003; Janowiak, 1991). The TRMM algorithm 3B43 combines three independent precipitation fields from the TRMM instrument package—the monthly average TRMM Microwave Imager (TMI) estimate, the monthly average Special Sensor Microwave/Imager (SSM/I) estimate and the pentad-average adjusted merged-infrared (IR) estimate—with the monthly accumulated Climate Assessment and Monitoring System (CAMS) or GPCP rain gauge analysis (Kummerow et al., 2000).

Although some satellite-only-based rainfall estimates are plagued with considerable bias over much of the African continent, the merged products which include ground measurements seem to be of superior quality. The performance of TRMM has been validated over Africa (Adeyewa and Nakamura, 2003) and West Africa in particular (Nicholson et al., 2003b) and the merged product 3B43 was found to be very well correlated with rain gauge measurements. McCollum et al. (2000) and Nicholson et al. (2003a) showed that the GPCP combined precipitation data set also out-performed the individual component satellite products. In general, the estimates are expected to be more reliable for the relatively politically stable western Sahel region than for the central and eastern Sahel, where a decline in ground measurements due to economic and political instability is likely to induce bias.

5. Methodology

The spatial–temporal analysis of the dynamics and trends in rainfall and vegetation greenness during the study period 1982–2003 is based on a sample size of 264 months, whereas the sample size of the shorter period 1998–2003 (validation period) amounts to 72 months. A definition of the Sahel region was derived from a 20-year-average NDVI rather than average annual precipitation as in Tucker et al. (1991), i.e. the Sahel was delineated by a minimum NDVI of 0.15 and a maximum of 0.4, which corresponds to the region with the steepest north–south gradient in vegetation greenness. However, any attempt to delineate the Sahel region by using long-term averages does not do justice to its fluctuating boundaries.

5.1. Pre-processing

Pre-processing of the NDVI time series had already been accomplished by the GIMMS group (see Section 4.1). For further analysis, the 8-bit GIMMS NDVI was converted into real NDVI. The gridded GPCP and TRMM precipitation data sets were re-projected to Albers Conical Equal Area Projection and resampled to match the 8 km resolution NDVI data set. While this procedure replicates a large number of GPCP pixels of the same value with no gain in spatial resolution in this data set, it enables to retain the finer spatial resolution of the NDVI data. Average daily (GPCP) or hourly (TRMM) precipitation rate estimates were converted into series of monthly and overlapping 2- and 3-monthly rainfall totals for later correlation and regression analyses with different time lag intervals.

5.2. Computation of trends

In order to determine spatial patterns of directions and rates of change, overall trends in NDVI and rainfall were computed for both the study and validation periods by fitting simple linear functions through the time series of each pixel and calculating the trend slopes. For the purpose of visualization, these were converted into changes in NDVI throughout the study period and expressed in percentage relative to the value of the linear trendline at the starting point of the time series.

5.3. Linear correlation and regression analyses

In order to test the strength of linear association between rainfall and NDVI, Pearson's correlation coefficients were computed for the two variables for each pixel with different time lags: NDVI versus rainfall of the current month with no time lag, NDVI versus cumulative rainfall of the current plus the previous month, and NDVI versus cumulative rainfall of the current plus the two previous months. The strongest linear correlation having been confirmed for NDVI and 3-monthly cumulative rainfall (consistent with findings of Nicholson et al., 1990), a linear regression analysis was carried out with NDVI as the dependent variable and 3-monthly cumulative rainfall as the independent variable. Local differences in the NDVI–rainfall relationship due to prevailing soil and vegetation types (Nicholson and Farrar, 1994) and their respective rain use efficiencies are taken into account by computing intercepts and slopes individually for each pixel. The regression equations establish a causal relationship between dependent and independent variables and allow the calculation of predicted values of maximum NDVI for each month and each pixel from the observed precipitation values.

NDVI residuals, the difference between observed and predicted NDVI, were then computed for each month and each pixel as done by Archer (2004) and Evans and Geerken (2004). The residuals represent that part of the observed NDVI value which is not explained by rainfall, provided that the computed linear regressions are accurate descriptions of the causal relationship between rainfall and NDVI for each individual pixel. In a scatter plot, they are represented by the distance of each point to the regression line. Residuals are assumed to contain noise, as well as, if present, the influence of any causative variables other than rainfall, which had been left out in the regression model. Any significant temporal trends in the residuals would point to an error of omission of a salient variable. To test for any long-term human-induced effects on vegetation greenness, be it positive (regeneration, re-forestation) or negative (desertification), trends were computed on the time series of NDVI residuals. The trend slopes were mapped in order to assess spatial patterns. As a measure of significance of the calculated trends, they were compared to their sigma errors and all trends exceeding the respective sigma error were labeled significant.

5.4. Extraction of temporal profiles

From the mapped trends in the residuals, hot spots displaying significant positive or negative trends were identified and temporal profiles of observed and predicted NDVI and NDVI residuals extracted for selected pixels (e.g., Figs. 6 and 7) and the dynamics of observed and predicted NDVI compared.

5.5. Validation

Validation of this regional-scale analysis is a difficult endeavor due to the large extent of the study area, and a field campaign to selected locations within the identified hot spots is planned for the next phase of this research stage of the project, with the aim of collecting detailed information on vegetation composition and land use and management. Thus far, a preliminary validation is obtained by comparing results of residual analyses based on a regression with GPCP and TRMM data for the validation period 1998–2003.

6. Results and discussion

6.1. Overall trends

For the period 1982–2003, the overall trend in monthly maximum NDVI is positive over a large portion of the Sahel region (Fig. 1), reaching up to 50% increase in the average NDVI in parts of Mali, Mauritania and Chad. It is understood, however, that averages are not very meaningful in this highly dynamic environment where considerable seasonal fluctuations around the mean are the norm. This result confirms previous regional-scale findings for the period 1982–1999 by Eklundh and Olsson (2003) and Olsson et al. (2005), who observed widespread positive trends of both time-integrated NDVI and NDVI amplitudes, and Anyamba and Tucker (2005), who maintained increases in growing season NDVI across most parts of the region. It is also in keeping with the global increase in net primary production due to climate change, postulated by Nemani et al. (2003). The positive trend in monthly maximum NDVI is accompanied by widespread increases in rainfall over the same period of time, with maximum positive slopes in northern Nigeria (Fig. 2). However, from a longer-term perspective, the observed increase can merely be interpreted as a return to more or less 'average' rainfall conditions that prevailed before the 1960s after an exceptionally dry period and does not even suffice, across the entire region, to cancel out the secular downward trend

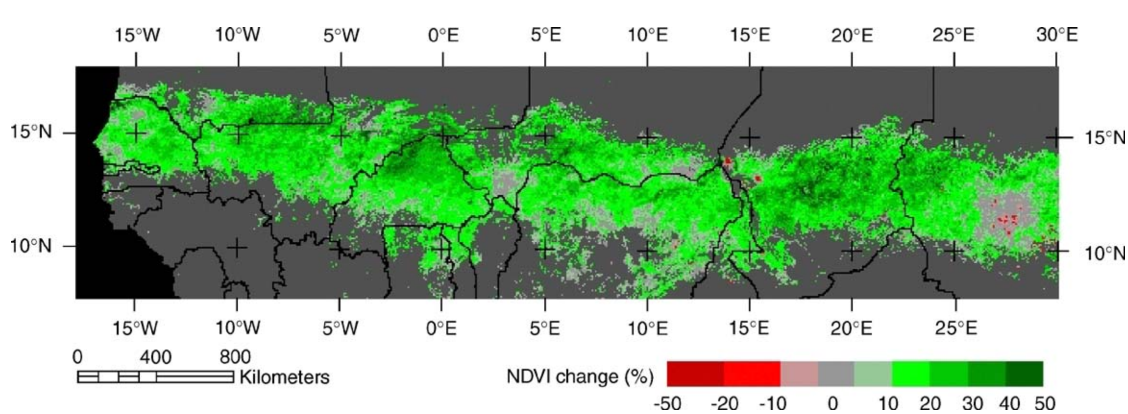


Fig. 1. Overall trends in vegetation greenness throughout the period 1982–2003 based on monthly AVHRR NDVI time series. Percentages express changes in average NDVI between 1982 and 2003.

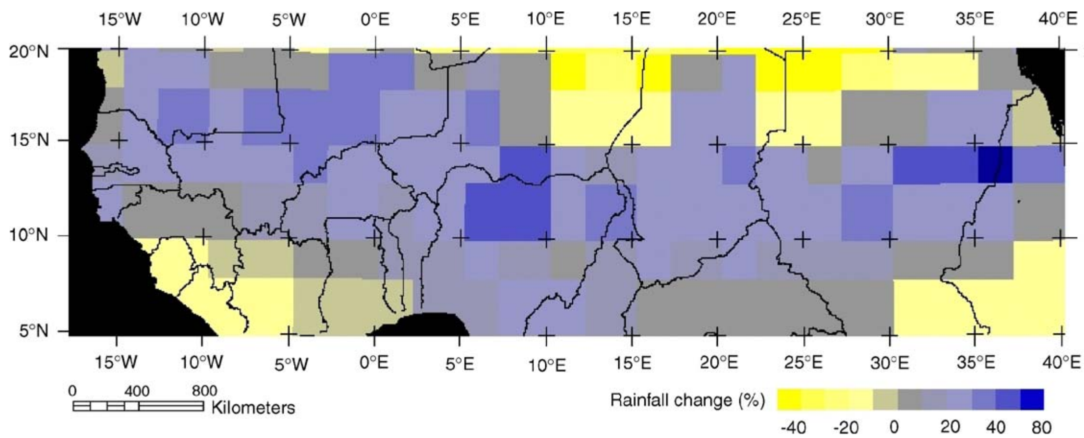


Fig. 2. Overall trends in monthly rainfall throughout the period 1982–2003 based on GPCP estimates. Percentages express changes in average GPCP-estimated rainfall between 1982 and 2003.

in rainfall (Hulme et al., 2001; Hulme, 2001; Nicholson, 2004). Indeed, the early- to mid-1980s saw the peak of Sahelian desiccation of this century, so that any analysis departing from there is on the rising limb of interannual and -decadal rainfall variability.

6.2. Correlation between NDVI and rainfall

Monthly maximum NDVI in the Sahel was found to be correlated best with rainfall accumulated over a period 3 months (current plus previous 2 months), which confirms earlier findings by Justice et al., 1986; Nicholson et al., 1990; Lotsch et al., 2003 and others that vegetation greenness in semi-arid environments is more strongly related to soil moisture, a function of rainfall accumulated over a period of time, than to instantaneous rainfall.

Correlation coefficients computed for NDVI and GPCP and TRMM exceed those found by Nicholson et al. (1990) based on rain gauge data, which might as well be a function of the NDVI data set employed. They are highly significant for the entire Sahel region ($P<0.05$), with stronger correlations in the southern Sahel than in the north. However, the presence of autocorrelation in both NDVI and rainfall data sets, which is a common phenomenon in time series and expresses persistence of variables, is likely to affect statistical relations and induce overestimation of the correlation coefficients (Granger and Newbold, 1974; Phillips, 1986). Durbin–Watson test statistics calculated for selected points yielded values between 0.4 and 0.7, all of which were significant ($P<0.01$) and confirm autocorrelation in the data sets. Although this phenomenon has possibly affected the magnitude of the correlation coefficients, it is not expected to have changed the overall spatial pattern of correlations (Fig. 3).

The zone of the highest correlation between NDVI and rainfall defines the extent of the semi-arid zone, where rainfall is the most important constraint to vegetation growth, while in the arid zone to the north, both variables are negligible and in the humid zone to the south, moisture availability is not the principal limiting factor for vegetation growth—hence, the zonality in correlation coefficients. Areas within the semi-arid zone where moisture availability is more a function of exogenous stream flow, such as the Niger delta, stand out of the zonal pattern by their lower correlation coefficients.

6.3. Residual analysis

The spatial pattern of trends in the NDVI residuals reveals large areas without significant trends, i.e. areas in which actual trends in vegetation greenness correspond closely to what is expected from the trends in rainfall dynamics, and considerable areas of positive residual trends, i.e. areas in which the vegetation has been greening up more than explained by rainfall alone (Fig. 4). These 'positive hot spots' are spatially coherent and comprise, among others, parts of Senegal, Mauritania, Mali, Niger, the Central Plateau of Burkina Faso and large portions of Chad. While the greening in the Niger delta of Mali might be explained by an expansion of irrigation, different explanations must be found for the Central Plateau of Burkina Faso, which had been identified as a prime example of the desertification crisis some 20 years ago (Pearce, 2002). Here, a recovery of vegetation greenness beyond what would be expected from the recovery of rainfall conditions alone might be due to increased investment and improvements in soil and water conservation techniques, such as contour bunding, in response to the drought crisis experienced by farmers (Reij et al., 2005). The importance of human factors, including decisions on production strategies and land use, in contributing to environmental and vegetation changes at long time scales is also stressed by Rasmussen et al. (2001) in an analysis of vegetation development on fossil dunes in northern Burkina Faso.

In Niger, positive trends in NDVI residuals are observed in the Tahoua and Maradi regions, centering around the area of 'Projet Keita', an extensive rural development

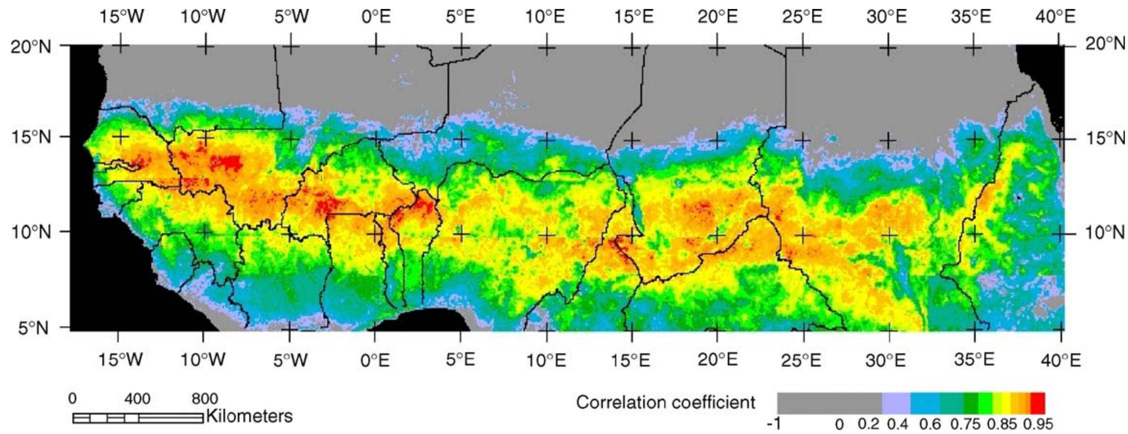


Fig. 3. Linear correlations of monthly NDVI with 3-monthly cumulative rainfall based on GPCP estimates for the period 1982–2003. Note that both variables are highly correlated in the Sahel region.

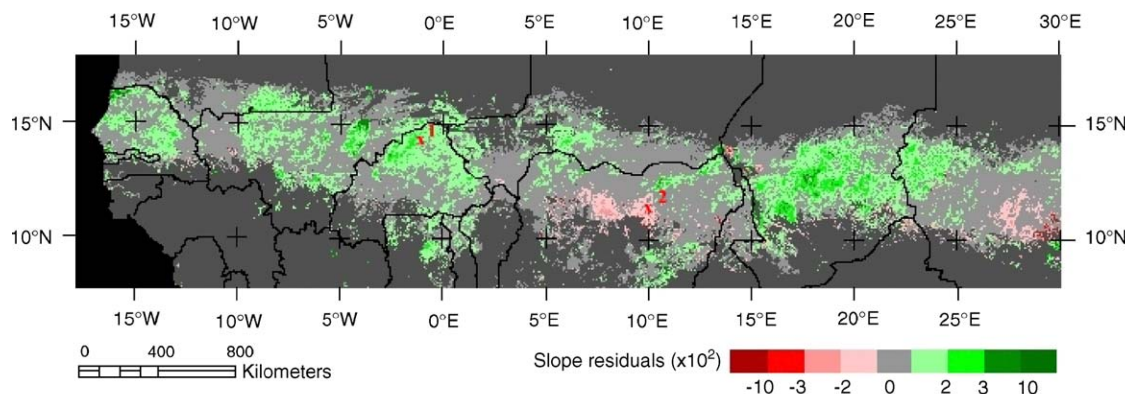


Fig. 4. Overall trends in the residual NDVI throughout the period 1982–2003 based on regression of vegetation greenness (AVHRR NDVI) on 3-monthly cumulative rainfall (GPCP estimate). Slopes of residual NDVI trendlines between 1982 and 2003 are expressed in units of NDVI $\times 10^4$. Locations of sites 1 and 2 are indicated, for which temporal profiles (Figs. 6 and 7) were extracted.

program with a focus on natural resource management and soil and water conservation which began in the early 1980s supported by the Food and Agriculture Organization (FAO) and the World Food Program (WFP) of the United Nations as well as the governments of Niger and Italy (FAO, 1994). Evidence of farmer-managed natural regeneration in this region of Niger was also confirmed by Chris Reij (personal communication, 2004), particularly along the road between Maradi and Dosso. In Chad, vegetation greening was observed among other places in the Chari–Baguirmi region, where the West African Pilot Pastoral Program has managed a few sites since 1994 to test a participatory approach to holistic rangeland management, the outcome of which was positively evaluated by pastoralists (Reij and Steeds, 2003).

Pixels showing negative trends in the NDVI residuals cover a considerably smaller area of the Sahel and are clustered in northern Nigeria and Sudan. Here, vegetation greening has fallen behind what would be expected from the increase in rainfall, which has been particularly sharp in northern Nigeria. A hypothetical explanation of what might be interpreted as human-induced land degradation in these areas is the neglect of good land use practices due to civil strife and conflict. Fig. 5 highlights that the trends found in the residuals are significant over most of the area, with insignificant results coinciding, as expected, with areas showing negligible trends in the residuals.

Temporal profiles extracted for selected pixels representative of positive, negative and negligible trends in the residuals (Figs. 6 and 7) show that removing the effects of rainfall from the NDVI time series did not completely remove the seasonality, part of which may be attributed to the seasonality in other environmental factors such as temperature. A comparison of predicted and observed vegetation dynamics illustrates, in the case of a Burkina Faso location, the gradual 'overtaking' of the predicted NDVI by the observed NDVI, notably in the peaks. The example of northern Nigeria shows a reverse dynamic, with the observed NDVI progressively falling behind the predicted one, both in the peaks and valleys of the profile. Owing to the characteristics of a less arid climate, the dynamics of vegetation greenness is smoother and displays less year-to-year variability in the example from northern Nigeria than in the example from Burkina Faso. The trends

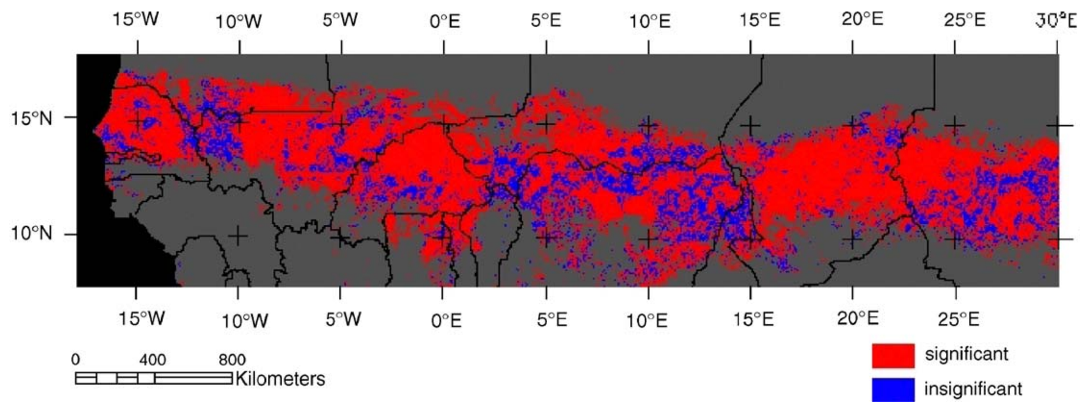
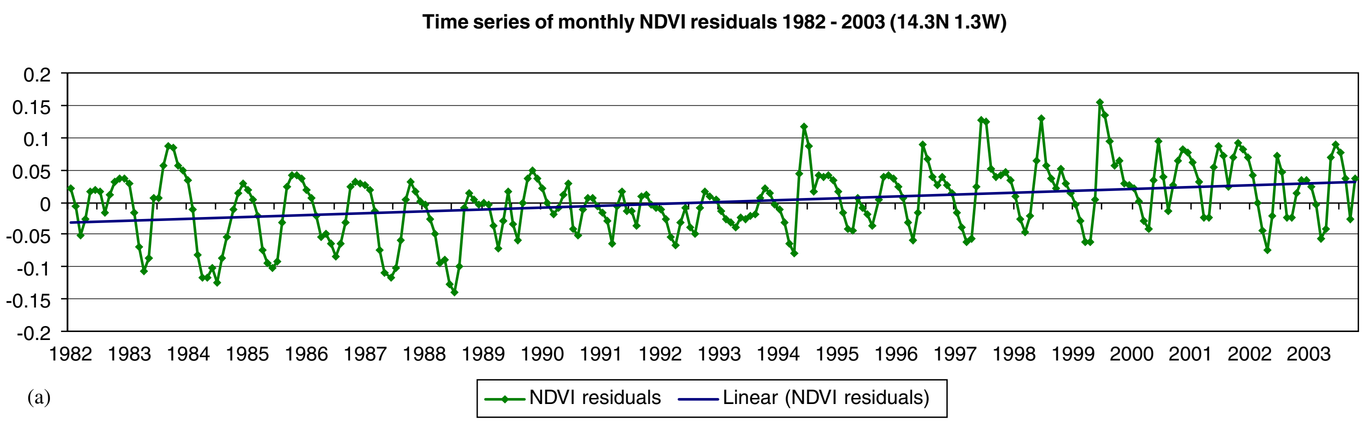
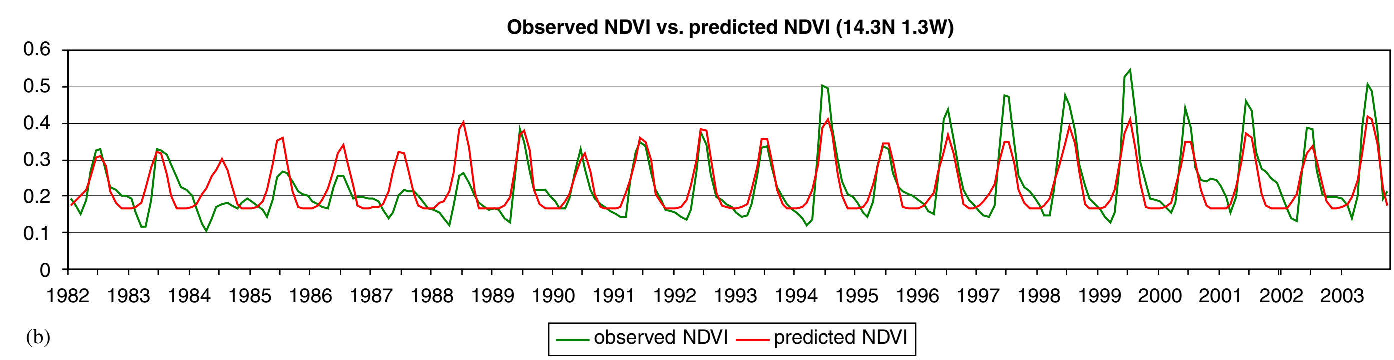


Fig. 5. Significances of trends in the residual NDVI time series show significant results over most of the study area. Trends are termed 'significant' for pixels in which trend slopes exceed the respective sigma errors and 'insignificant' for pixels in which sigma errors exceed trend slopes.



(a)



(b)

Fig. 6. Temporal profiles for location (1) (see Fig. 4) with significant positive trend in the residual NDVI (Central Plateau, Burkina Faso). (a) Residual NDVI time series and linear trendline. (b) Time series of observed and predicted NDVI.

found in the residuals, however, cannot be attributed to zonal effects, as an analysis of a number of temporal profiles from different latitudes revealed (not shown).

6.4. Comparison of results based on GPCP and TRMM

Rainfall trends for the period 1998–2003, whether based on GPCP or TRMM data, differ from rainfall trends for the longer period 1982–2003 in that negative trends are present in the northernmost parts of the Sahel, notably extending from the northern Tahoua region in Niger to the east. Droughts intensified in these regions during the past 5 years, whereas the central and southern parts of the Sahel experienced mostly increasing rainfall (see also Nicholson, 2005). Correspondence between the two data sets is high, with correlation coefficients ranging from 0.9 to 0.99, which can be explained by the fact that both data sets rely on input data partly from the same sources (see Section 4.2).

Consistent with the observed trends in rainfall for the period 1998–2003, the respective NDVI trends show a decrease in vegetation greenness in a band along the

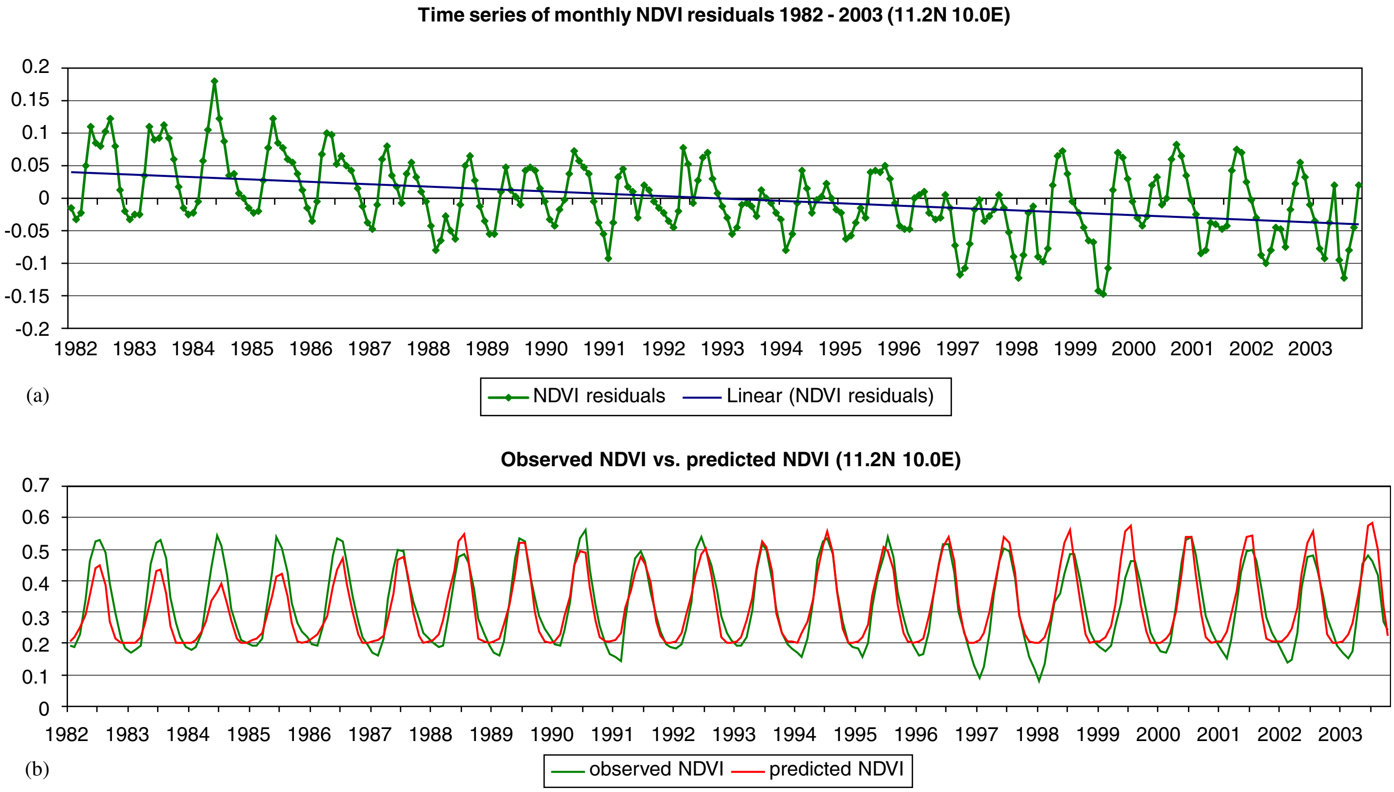


Fig. 7. Temporal profiles for location (2) (see Fig. 4) with significant negative trend in the residual NDVI (northern Nigeria). (a) Residual NDVI time series and linear trendline. (b) Time series of observed and predicted NDVI.

northern margin of the Sahel (Niger, Chad and Sudan). This trend, however, is not as well defined as the trend for the longer time series, since it comprises only the period of 'most greening'.

The trends in NDVI residuals, after removing the effects of rainfall from the NDVI data set, display very similar spatial patterns for regression analyses based on either GPCP or TRMM. Although these trends for 1998–2003 are not statistically significant over most of the area—i.e. the trends themselves are smaller than the sigma error, the main point here is to show the close agreement between results based on different sources of rainfall estimates, which can be seen as a means of validation of the methodology and increases the confidence that the NDVI residuals and trends therein contain more than just random noise.

7. Conclusions

This research adds to a series of coarse-resolution studies on the Sahel which refute claims of widespread human-induced land degradation at a regional scale, e.g., Prince et al. (1998), Tucker and Nicholson (1999); Hellden (1991) and Eklundh and Olsson (2003). Rather, a greening of the Sahel expressed in positive trends in NDVI indicates a net increase in biomass production during the period 1982–2003, which challenges the notion of irreversible desertification in the Sahel. Whether this greening trend is a return to pre-drought conditions or a transition to a new equilibrium state with a different vegetation composition, however, is unclear and can only be established with detailed field work at local scale and analysis of finer resolution spatial data from LANDSAT and MODIS.

Rainfall emerges as the dominant causative factor in the dynamics of vegetation greenness in the Sahel at an 8 km spatial resolution. However, the presence of spatially coherent and significant long-term trends in the residuals suggests that there might be another, weaker, causative factor. Since the Sahel is a 'cultural landscape' (Rasmussen et al., 2001), which is driven not only by climatic but also human factors, it is conceivable that the trends found in the residuals might be attributed to a 'human signal', as evidence from the literature suggests for particular regions (see Section 6.3). While short-term impacts such as pests can cause rainfall-independent deviations of the NDVI in individual years, long-term trends are more likely to be induced by human factors, such as changes in land use, exploitation of natural resources, production strategies and conservation efforts. Field studies in selected sites are required to confirm this hypothesis and to contribute to the understanding of processes and causes at work in particular local contexts.

Throughout most of the Sahel, there are no signs of large human-induced land degradation at this scale of observation—which does not mean that pockets of land degradation are not present at local scales. Only parts of northern

Nigeria and Sudan show areas where human impact hypothetically inhibited a greening trend in the order of magnitude expected from the positive trend in rainfall conditions.

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