Journal of Arid Environments 63 (2005) 556–566
Journal of Arid Environments
www.elsevier.com/locate/jnlabr/yjare

A recent greening of the Sahel—trends, patterns and potential causes

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Available online 4 May 2005

Abstract

For the last four decades there has been sustained scientific interest in contemporary environmental change in the Sahel (the southern fringe of the Sahara). It suffered several devastating droughts and famines between the late 1960s and early 1990s. Speculation about the climatology of these droughts is unresolved, as is speculation about the effects of land clearance on rainfall and about land degradation in this zone. However, recent findings suggest a consistent trend of increasing vegetation greenness in much of the region. Increasing rainfall over the last few years is certainly one reason, but does not fully explain the change. Other factors, such as land use change and migration, may also contribute. This study investigates the nature of a secular vegetation trend across the Sahel and discusses several potential causative factors.

Keywords: Vegetation change; Sahel; Desertification; Remote sensing; Migration

1. Introduction

Discussion of the relative importance of climatic and human causes of vegetation change in the Sahel began in the 1930s and is still continuing (Stebbing, 1935, 1937,

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0140-1963/$ - see front matter
doi:10.1016/j.jaridenv.2005.03.008

1938; Aubreville, 1949; Tucker and Nicholson, 1999). Discussion intensified after more recent droughts in the 1970s and 1980s (Lamb, 1982; Olsson, 1993; Nicholson, 1994, 2000, 2001; Hulme, 2001). 'Over-cultivation', 'overgrazing', and excessive exploitation of wood fuel have repeatedly been invoked. Recent results from global climate modelling, however, suggests a strong link between sea surface temperature (SST) anomalies and rainfall in the Sahel region. Using a GCM and a number of SST scenarios, Giannini et al. were able to reproduce much of the observed rainfall variation (1930–2000) in the Sahel and also explain some 25–35% of inter-annual rainfall variations (Giannini et al., 2003). Local to regional interaction between vegetation and rainfall was also shown to be linked to the variability of Sahel rainfall (Zeng et al., 1999).

The effects of the severe drought in 1983–1984, affecting the entire region were documented using satellite imagery by several authors, notably Tucker et al. (1991). They showed a marked southward shift of the edge of the desert, but noted that it would require long-term observations to prove a secular change, given the notoriously variable climate of the area. More recent studies in the Sahel have suggested secular trends of change, many related to vegetation and land use, in selected case studies (Mortimore and Adams, 2001; Reij and Thiombiano, 2003), at a national scale (Niemeijer and Mazzucato, 2002) and even at the regional to sub-continental scale (Eklundh and Olsson, 2003). In this study we analyse more closely the pattern of vegetation change across the Sahel and we discuss possible causative factors behind the observed trend. Climate variation is clearly one of these causative factors, but not the only one. The aim of this paper is therefore also to discuss and hypothesize possible factors other than climate even though we are unable to determine clear links between vegetation change and these factors.

2. Materials and methods

For the purpose of analysing vegetation dynamics at sub-continental scale, satellite data from the NOAA AVHRR sensing system for the period 1982–1999, using the Normalized Difference Vegetation Index (NDVI) were used. NDVI has been confirmed by many studies to be responsive to several vegetation variables, such as leaf area index (LAI), vegetation greenness and absorption of photosynthetically active radiation (Myneni et al., 1997; Sellers et al., 1997). These data are particularly well suited to the study of semi-arid regions because: (1) NDVI becomes saturated at LAI levels higher than 3–5 (Prince, 1991a, b; Field et al., 1995), and (2) atmospheric contamination (particularly clouds) of the data is less of a problem in semi-arid regions than in more humid ones (Chappell et al., 2001). The time series was restricted to the period 1982–1999 because after 1999 there was a significant shift in the NDVI values (Eklundh and Olsson, 2003), probably caused by late afternoon overpass of NOAA-14 (Gutman, 1999).

Smooth annual time series of 8×8 km NDVI grid cells were created for the Sahel region (8°–24°N latitude) using the NASA/NOAA Pathfinder AVHRR Land (PAL) database (James and Kalluri, 1994) and the TIMESAT processing scheme (Jönsson and Eklundh, 2003, 2004). This method generates smooth time series comprising several attributes of the dynamics of the vegetation, such as the time-integrated value and the amplitude over a base level (Eklundh and Olsson, 2003). Based on the time-integrated values and the amplitude values of the smooth time series, the trend over the 1982–1999 period was determined for every grid cell, using least-squares estimation.

The NDVI time series data were then compared with monthly rainfall observations (July–September) for the same period. The rainfall data were tested for consistency over time and only stations with less than two missing observations in each of the time periods 1980–1989 and 1990–1999 were included in the analysis. For the statistical analysis of relationships between rainfall and NDVI, a 3×3 grid cell window around each climate station was extracted from each year in the time series. This correspond to an area of 24×24 km from which the NDVI values were averaged and compared with the rainfall data. The validity of this comparison is further discussed later in this paper.

3. Results

The result of the analysis of the time series of satellite data showed a geographically consistent pattern of increasing NDVI across the Sahel zone, Fig. 1. The trend was apparent in both the time integrated values and the amplitude values but differed substantially in its geographical distribution between the two data types.

The increase shown in Fig. 1 is remarkable, particularly in the case of the integral where many areas have more than doubled the annual NDVI integral in the period. The distinct difference between the geographical patterns of the amplitude and the integral trend is also noteworthy. The increase in the amplitude is restricted to a rather narrow belt in the northern Sahel while the integral shows a wider belt of increase most of which is further south in a rather indistinct latitudinal belt.

The difference between these two patterns is related to the fact that NDVI is primarily related to the amount of green biomass but saturates when the vegetation cover reaches high levels (Field et al., 1995). Thus, the amplitude will only increase up to a certain level whereas the integrated NDVI can continue to increase in areas of more abundant vegetation due to increased seasonal length and higher NDVI-values during the time of the season when NDVI is below its saturation level.

Changes in vegetation type may also affect the changes. In semi-arid grasslands and woodlands, annual and perennial species differ in their NDVI response (Karnieli et al., 2002). In particular, the increasing amplitude trend may indicate a change in the dominant vegetation cover type.

Several previous studies have shown a positive relationship between NDVI and rainfall (Prince, 1991a, b; Nicholson and Farrar, 1994). The pattern of vegetation and rainfall trends indicated by the rainfall stations in Fig. 1, may suggest a positive link in some areas but not consistently. Only eight out of 40 rainfall observations showed a statistically significant (95%) increase of rainfall between 1982–1990 and 1991–1999 periods. Further analysis of this relationship does not indicate an overall relationship between rainfall increase and vegetation trend, Figs. 2 and 3. From

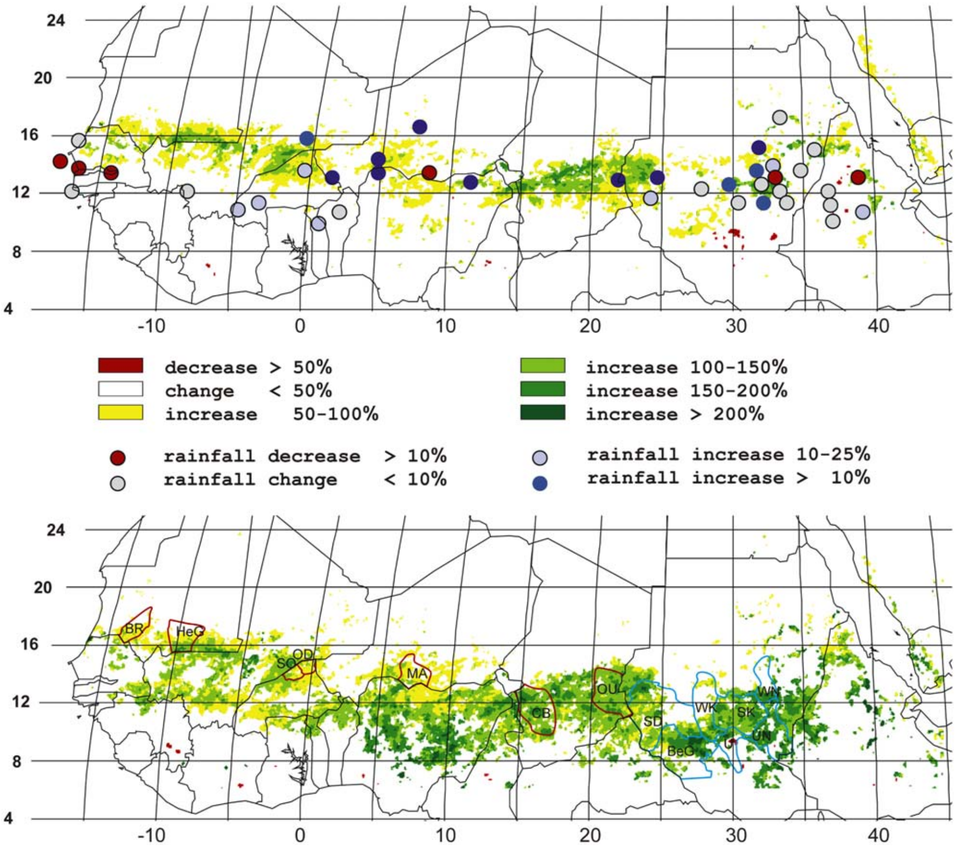

Fig. 1. The results of trend analyses of time series of NDVI amplitude (top) and NDVI seasonal integral (bottom) of NOAA AVHRR NDVI-data from 1982 to 1999. Areas with trends of <95% probability in white. Data from 40 climate observation stations, showing percent change between the periods 1982–1990 and 1991–1999, have been superimposed on the top figure. Blue areas in the lower figure refer to regions in Table 1 and red areas to regions used in Fig. 4.

Fig. 2 it is evident that there is a consistent positive trend of NDVI for almost all rainfall stations, but only about half of them showing a positive rainfall trend. From Fig. 3 it is evident that the NDVI trend is very strong, from -1 to $+1$ standard deviation, while the rainfall trend is less clear.

4. Discussion

Rainfall in the Sahel has generally increased over the last 5–8 years (Hulme, 2001), but the strong trend of increasing vegetation cover can only partly be explained by

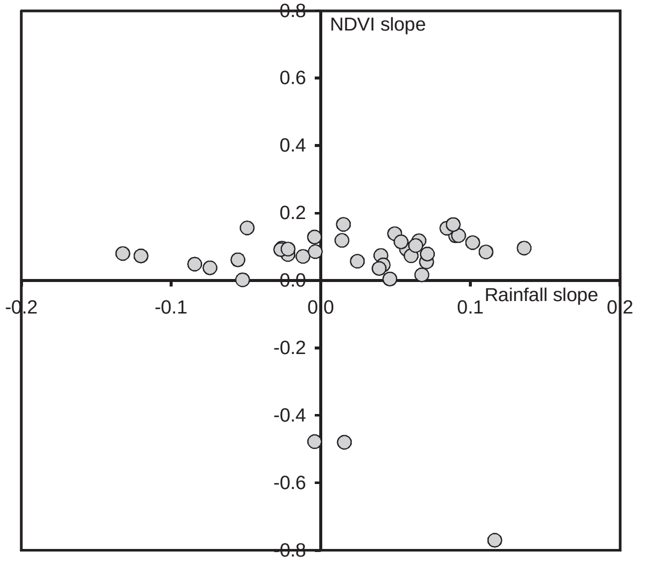

Fig. 2. Least-squares estimated slope of NDVI versus least squares estimated slopes of rainfall time series for the 40 stations in Fig. 1. The NDVI values are the average of a 3×3 grid cell window covering each station.

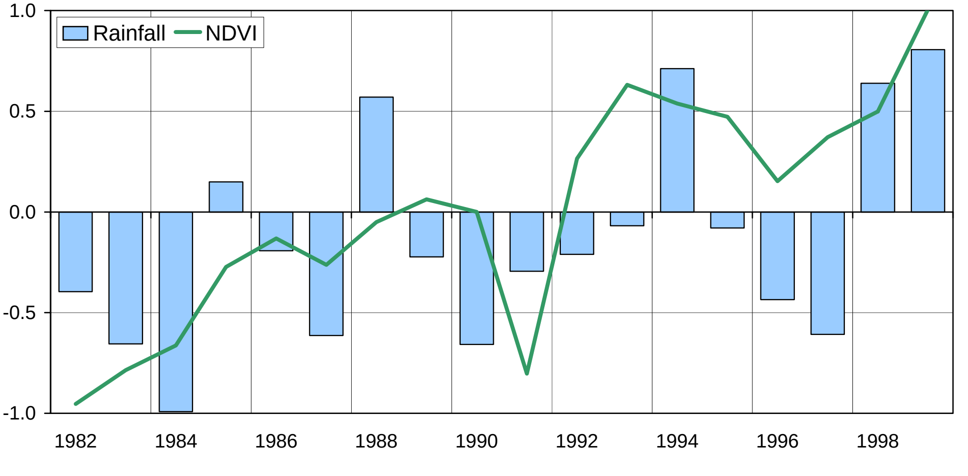

Fig. 3. Average Z-scores (expressed as standard deviations) of NDVI and rainfall for the 40 stations in Fig. 1. The NDVI values for the 40 stations are the average of a 3×3 grid cell window covering each climate station.

rainfall increase. One obvious problem relating rainfall and vegetation change is the coarse spatial resolution (8 km) of the vegetation information. This makes a direct comparison with rainfall in one discrete location difficult, particularly considering the erratic nature of rainfall in arid regions. Nevertheless, other factors such as changes in land use and agricultural practices might contribute to the observed trend. Possible land use factors potentially contributing to increasing vegetation cover include: changed land management (grazing, cropping, manuring), new agricultural policies (removing subsidies on agricultural inputs), fuel-wood collection and demographic trends.

After many years of dwindling food production in the Sahel, only two countries show signs of improved agricultural performance. According to national statistics (FAO, 2003), Burkina Faso and Mali have increased their production of millet (kg/capita) by 55% and 35%, respectively, since 1980, while the other Sahelian countries show decreases in their production. In the case of Burkina Faso, this has also been confirmed in other studies (Niemeijer and Mazzucato, 2002). However, most of the observed vegetation changes are located in the northern fringes of cultivation where rangeland rather than cropland dominates. In northern Burkina Faso a study of vegetation change has demonstrated that recovery of vegetation cover started immediately after the drought year of 1984 (Rasmussen et al., 2001). These results were obtained through analysis of aerial photos, satellite images and interviews with local people, which generally produce the same result, namely that the cause is an increase in rainfall, relative to the drought period of the 1970s.

NDVI data have often been used for assessing crop yields (Maselli et al., 2000). In order to test the relationship between increasing NDVI and agricultural output, more detailed data for regions (marked by red lines in Fig. 1) corresponding to significant NDVI increases were obtained. Data on agricultural productivity (millet yield, kg/ha) within these regions were obtained from the Africa Data Dissemination Service (ADDS, 2003) for the years 1982–1999. The time-integrated NDVI values were extracted for the same regions and years, Fig. 4. It is obvious from the graph that there is no clear relationship between millet yield and NDVI for these regions ($R^2 = 0.10$). The reason for a lack of statistically significant relationship can be either that the data on agricultural productivity is not good enough, that the fields are too small to influence the coarse overall NDVI signal. It could also indicate that there are other reasons for the vegetation trend than increased crop yields, e.g. land use changes.

In some parts of the Sahel rural to urban migration may partly explain the vegetation trend. In order to investigate patterns of rural-to-urban migration data on the size of cities were obtained. These data are of unknown quality and compiled from several different sources. If, however, we dare to analyse these data, a very interesting pattern of extremely high growth rates for many cities emerge (Fig. 5). Based on the analysis of data from 130 cities, the annual growth rate was found to be much higher than what can be expected from analysis of general national demographic data (Fig. 6). We must stress the uncertainty of the data, but the trend of rapid urbanization is well known. Rural-to-urban migration is a very common coping strategy in Sub-Saharan Africa (Schrieder and Knerr, 2000; Mortimore and Adams, 2001; Tiffen, 2003). Money sent home by migrant workers is sometimes the most important source of income in rural households. As a consequence for the agricultural sector, labour might become a shortage but other inputs (e.g. seeds, machinery and fertilisers) might very well increase. Labour

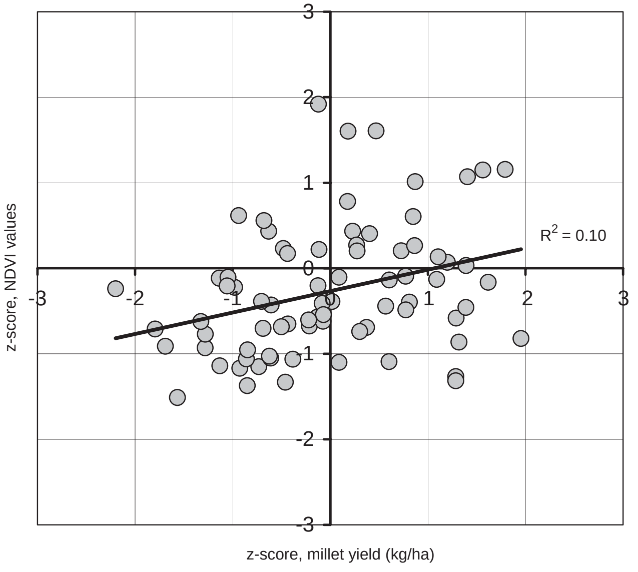

Fig. 4. Time-integrated NDVI values plotted against millet yield for the 8 regions shown in red in Fig. 1 for the time period 1982–1999. Number of data points = 76, data for 1982–1999 (missing values = 68). Data from ADDS (2003).

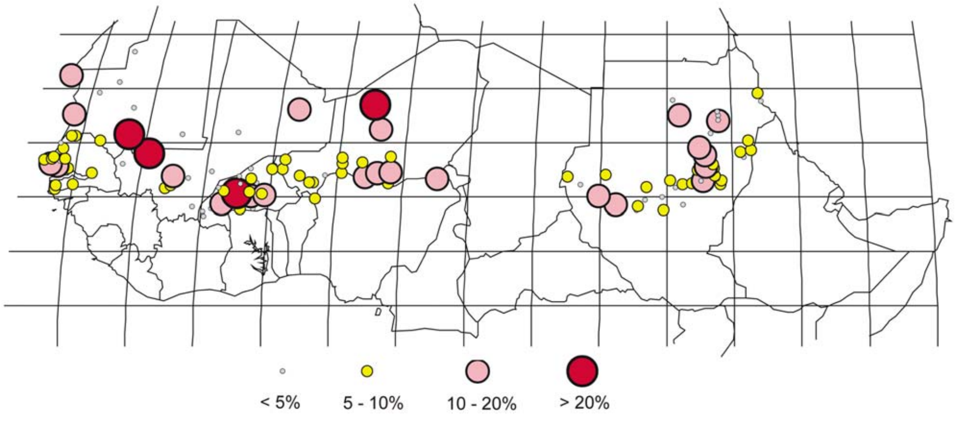

Fig. 5. Population growth rates of cities in six Sahelian countries*. The circles indicate annual growth rates for 130 cities during the 1980s and 1990s. Data for Chad and Ethiopia are missing.

is often one of the most important constraints to agriculture in drylands (Ouedraogo and Zombre, 2001; Osbahr and Allan, 2003; Visser et al., 2003; Warren et al., 2003). Widespread vegetation increase, due to reduced area under cultivation and/or increasing inputs on cropland, is therefore a possible result of increased rural-to-urban migration and increased dependence on remittances.

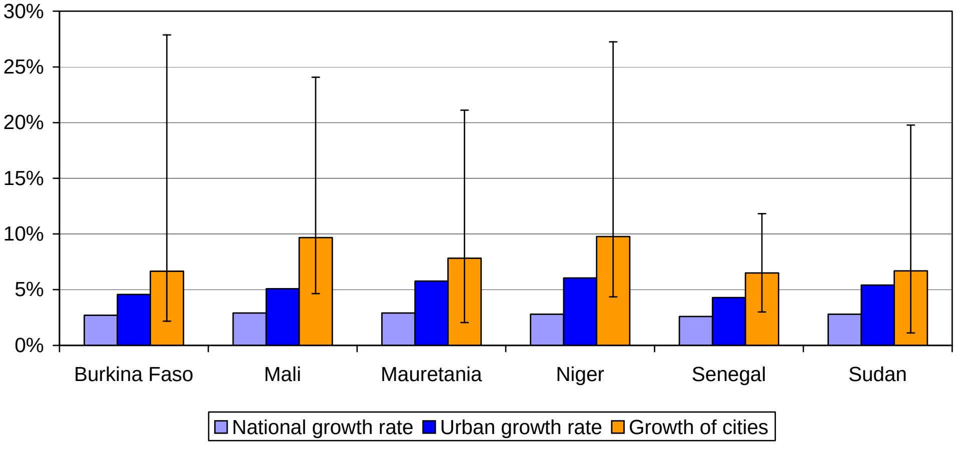

Fig. 6. Population growth rates for six Sahelian countries (Data for Chad and Ethiopia are missing), expressed as (% year) of (a) national growth rate (left column), (b) urban growth rate from official source (FAO 2003), (central column) and (c) growth rates of city populations from different sources with minimum and maximum values of data indicated by the error bars (right column). Different sources have been used and after consistency check the following data were selected: for Burkina Faso www.citypopulation.de (1985 and 1996), populations.com (1998), www.library.uu.nl (2002), for Mali www.citypopulation.de (1976 and 1987), www.world-gazetter.com (1998 and 2003), for Mauretania www.citypopulation.de (1977, 1988 and 2000), www.world-gazetter.com (2003), for Niger: www.citypopulation.de (1977, 1988 and 2000) www.world-gazetteer.com (2003), for Sudan www.world-gazetter.com (1983 and 2003), for Senegal www.citypopulation.de (1976 and 2001).

Another possible factor is political unrest and armed conflicts, particularly in the Sudan. The vast belt of significantly increasing vegetation across the central Sudan corresponds to a large extent to provinces with large numbers of internally displaced people. Totally in the seven Sudanese provinces shown in Fig. 1, almost 2 million people are internally displaced, corresponding to about 24% of the population (Table 1). Being internally displaced, means that people have fled their homes and live elsewhere away from their normal means of incomes, often in the outskirts of towns. As a consequence, agriculture is neglected and livestock dispersed. The consequence for the vegetation is often abandoned fields and reduced grazing pressure.

5. Conclusion

To conclude, the strong secular trend of increasing vegetation greenness over the last two decades across the Sahel cannot be explained by a single factor such as climate (Nemani et al., 2003). Increasing rainfall does explain some of the changes but not conclusively. Another potential explanation could be improved land management, which has been shown to cause similar changes in vegetation response elsewhere (Runnström, 2003). However, the fact that millet yield and increasing

Table 1
Number of internally displaced persons (IDP) in central and South Sudan

Map	Province	IDPs	Population	IDPs (%)
SD	South Darfur	203,000	1,083,000	19
BeG	Bahr el Ghazal	683,600	1,595,800	43
WK	West Kordofan	85,500	1,424,400	6
SK	South Kordofan	470,000	1,210,000	39
U	Unity	70,000	287,000	24
UN	Upper Nile	390,000	1,261,100	31
WN	White Nile	58,000	1,253,100	5

The first column refer to the regions indicated in Fig. 1.
Source: IDPs from UNOCHA (2003). Population figures from Helders (2003).

vegetation greenness were unrelated does not support this explanation. The third factor, land use changes as a result of migration, is a plausible contributing explanation, but more empirical research is needed to verify this.

Although it is evident that the observed vegetation trend is the result of a complex combination of social and environmental factors, most of which are to be understood better, there are already some important policy implications. The observations imply that there may be a potential for improvement in agricultural productivity and thus in human welfare because rainfall has increased in some areas. A positive climatic and vegetation trend should not be interpreted as an argument for decreased support for what remains the world's poorest region but instead be seen as a potential impetus for agricultural development.

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