Exploring Relationships between Rainfall and Vegetation Dynamics in the Sahel Using Coarse Resolution Satellite Data

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Abstract – This research investigates temporal and spatial patterns of vegetation greenness and explores relationships between rainfall and vegetation dynamics in the Sahel, based on analyses of NDVI time series and gridded precipitation estimates at different spatial resolutions.

Keywords: rainfall, vegetation, land degradation, Sahel

1. INTRODUCTION

The West African Sahel, a semi-arid transition zone between the arid Sahara in the north and the subhumid tropical savannas in the south, is a dynamic ecosystem that responds to fluctuations in climate and anthropogenic land use patterns. The climate of the Sahel is characterized by a marked contrast between a long dry season and a short humid season in the northern hemispheric summer, with increasing scarcity, variability and unpredictability of rainfall from south to north. Although variability in rainfall and recurring droughts are normal phenomena of the semi-arid climate, the droughts that affected the Sahelian region in the late 1960s through the 1980s were unprecedented in this century in length and impact (e.g. Tucker and Nicholson, 1999). Famine conditions and land degradation became widespread during these droughts, the latter being frequently interpreted as irreversible change or 'desertification'. However, contrary to largely anecdotal assertions of wide-spread 'desertification' in the Sahel (e.g. Lamprey, 1975 [reprinted 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 has been interpreted as a recovery of the vegetation from the great Sahelian droughts (e.g. Tucker and Nicholson, 1999; Eklundh and Olsson, 2003). This recently observed greening trend has challenged notions of irreversible damage inflicted on the Sahelian ecosystem and renewed the debate about the concept of desertification (Herrmann and Hutchinson, 2005), in which two diametrically opposed positions are represented by those who see human mismanagement as the root cause of irreversible desertification (LeHouerou, 2002) and those who refute the concept of desertification altogether and stress the importance of natural fluctuations in rainfall and consequently vegetation response (Tucker and Nicholson, 1999; Eklundh and Olsson, 2003).

While the relationship between vegetation and rainfall in semi-arid environments has been studied extensively, particularly in the Sahel, few efforts have been made to explicitly disentangle the effects of rainfall and human impact on vegetation dynamics. The objectives of this research are to further explore trends in vegetation greenness and precipitation and their spatial patterns in the Sahel and to address the question of a potential 'human signal' in vegetation dynamics by developing a method of removing the climate signal from vegetation greenness time series.

2. DATASETS USED

2.1 Vegetation greenness data

Vegetation greenness is expressed by the Normalized Difference Vegetation Index (NDVI), a remotely sensed measurement of spectral reflections in the red and near-infrared wavelength regions [(NIR-red)/(NIR+red)] sensitive to the presence, density and condition of green vegetation. The NDVI is the common and, despite some shortcomings, most widely used vegetation index. Therefore, relatively continuous long term time series starting in the early 1980s are available. In this study, we used NDVI datasets from two different satellite sensors: the Advanced Very High Resolution Radiometer (AVHRR) sensor on board the National Oceanographic and Atmospheric Administration (NOAA) polar orbiting satellite series and the Système Probatoire pour l'Observation de la Terre Végétation sensor (SPOT/VGT).

NOAA AVHRR sensors have been operational for more than two decades and offer a length of record that is unmatched. We used an 8-km spatial resolution monthly maximum value composite of the NDVI for the period 1982 to 2003, preprocessed by the Global Inventory Modeling and Mapping Studies (GIMMS) Group at NASA's Goddard Space Flight Center. This NDVI time series 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).

The SPOT Végétation (VGT) sensor has only been operational since 1998 on two SPOT missions (http://vegetation.cnes.fr/). The VGT NDVI product used in this study differs from the AVHRR NDVI in its finer spatial resolution of 1 km, narrower band widths in the red and NIR wavelengths meant to enhance vegetation discrimination, and the minimal preprocessing of the dataset compared to the AVHRR NDVI time series (e.g. monthly maximum value compositing but no atmospheric corrections).

2.2 Precipitation estimates

Since rain gauges are sparse and of varying reliability throughout the Sahel (Nicholson et al., 2003), this study employed gridded satellite precipitation estimates, which combine satellite observations from different sources and available ground measurements into area averaged precipitation fields. The principles behind these merged datasets and the combination methodology are explained in more detail in Xie and Arkin (1997).

For establishing a relatively long term relationship between rainfall and vegetation greenness, a combined precipitation dataset from the Global Precipitation Climatology Project at a spatial resolution of 2.5° (GPCP Version 2) was used for time period 1982-2003. The GPCP product integrates, in weighted averages, infrared observations from the Geostationary Operational Environmental Satellite (GOES), the 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).

The 10-day rainfall estimates (RFE), produced by NOAA/CPC (Climate Prediction Center) to support the USAID/FEWS (Famine Early Warning System) project in drought and flood risk monitoring for Africa, provided a shorter term, but finer spatial resolution gridded rainfall dataset. The RFE are based on Meteosat satellite data, Global Telecommunication System (GTS) rain gauge reports, and microwave data from the SSM/I and the Advanced Microwave Sounding Unit (AMSU) (Xie and Arkin, 1997). A combination of versions 1.0 and 2.0 of the dataset allowed the creation of a 0.1° resolution time series that matches the length of the VGT NDVI record.

3. METHODS

3.1 Establishing coarse-scale rainfall-NDVI relationships for the period 1982 to 2003

Since 3-month cumulative rainfall had already been found to be correlated best with NDVI for the region under study (Herrmann et al., 2005 ; consistent with findings of Nicholson et al., 1990), the rainfall estimates from GPCP and RFE were converted into a time series of monthly overlapping 3-month cumulative totals and resampled in order to fit the spatial resolution and geographic projection of the NDVI time series.

With the aim of establishing a causal relationship between rainfall and NDVI, a linear regression analysis was carried out for the entire Sahel on the longest available time series, with the AVHRR NDVI as the dependent and the GPCP cumulative rainfall totals as the independent variable. Local differences in the NDVI-rainfall relationship due to prevailing soil and vegetation types are taken into account by computing intercepts and slopes individually for each pixel. The regression equations allow the calculation of predicted values of 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 (Archer, 2004). The residuals present 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. They 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. Temporal trends in the NDVI residual time series were calculated and mapped with the aim of establishing areas in which significant trends in the residuals would point to an error of omission of a salient variable.

3.2 Application of the method to finer-scale datasets for the period 1998 to 2003

In order to test the possibility of expanding the analysis to higher spatial resolution datasets, with the drawbacks of their limited temporal availability, a comparison of higher and lower resolution NDVI and rainfall data was carried out at the example of seven selected locations. To that end, temporal profiles were extracted from all datasets, which had previously been regridded to a spatial resolution of 8km.

The AVHRR NDVI and the VGT NDVI time series were compared and correlated against each other in order to show agreement and discrepancies of the two data sets from different sources. The same was done for the two rainfall estimates, as well as different combinations of rainfall versus NDVI. Predicted NDVI time series were calculated using the linear regression between NDVI and rainfall established from the longer time series (see 3.1) and linear regressions calculated from the shorter time series. The coefficients of these regressions were compared to each other in order to evaluate the applicability of the rainfall-NDVI relationship determined using the longer, coarse-resolution time series, which is assumed to be more accurate due to the length of the record, to the shorter, but higher spatial resolution, time series of VGT NDVI and RFE rainfall estimates. Differences between observed VGT NDVI values and NDVI values predicted from RFE rainfall using the linear relationship established from AVHRR NDVI and GPCP rainfall estimates were calculated and compared to the residuals as computed in 3.1.

4. RESULTS AND DISCUSSION

4.1 Summary of findings from the coarse scale assessment

Overall positive trends in NDVI and rainfall over the period 1982 to 2003 were confirmed. Linear correlations between the two variables were found to be highly significant throughout the entire Sahel. Indeed, rainfall is the most important constraint to vegetation growth in this semi-arid zone, which justifies the attempt to predict vegetation greenness from rainfall estimates through linear regression (Herrmann et al., 2005).

The spatial pattern of trends in the NDVI residuals (Fig.1, last page), computed by subtracting observed from predicted NDVI values, reveals large areas without significant trends, i.e. areas in which actual trends in vegetation greenness correspond closely to what is expected form 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. These areas comprise parts of Senegal, Mauritania, Mali, the Central Plateau of Burkina Faso, southern Niger 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 two decades ago (Pearce, 2002). Here, a recovery of vegetation greenness beyond what would be expected from the recovery of rainfall conditions alone might be attributable to increased investment and improvements in soil and water conservation techniques (e.g. Reij et al., 2005).

Negative trends in the NDVI residuals are clustered in northern Nigeria and Sudan. Here, vegetation greening has fallen behind what would be expected from the increase in rainfall. 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.

4.2 Preliminary results from comparison of different datasets

Comparison of observed rainfall and vegetation dynamics from 1998 to 2003 showed marked differences between AVHRR and VGT NDVI as well as GPCP and RFE rainfall estimates, which are summarized in Figure 2. Overall, the VGT NDVI tends to be higher than the AVHRR NDVI and the GPCP rainfall data higher than the RFE. These differences, rooted in differences in data collection, resolution and calibration, are neither spatially nor temporally consistent and make a direct transfer of the rainfall-NDVI relationship computed from one dataset to the other problematic.

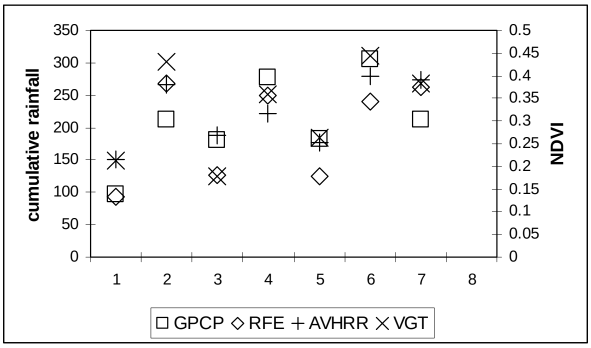

Figure 2. Average NDVI and cumulative rainfall for 7 selected sites during the period 1998-2003

The linear relationships between rainfall and NDVI for the period 1998 to 2003 tended to be similar for GPCP versus AVHRR and RFE versus SPOT for some points (Fig.3a, last page), encouraging the use of the supposedly more reliable regression equation based on the longer time series, but quite different for others (Fig.3b), making the use of this regression equation impossible. The same is true for the temporal pattern of the difference between observed and predicted NDVI for GPCP versus AVHRR and RFE versus SPOT.

5. CONCLUSIONS

From the coarse scale assessment, rainfall emerges as the dominant causative factor in the dynamics of vegetation greenness in the Sahel. However, the presence of spatially coherent and significant long-term trends in the NDVI residuals suggests that there is another, weaker, causative factor, possibly a 'human signal'. However, field studies in selected sites are required to confirm this hypothesis.

The results of the preliminary comparison of GPCP versus AVHRR and RFE versus VGT relationships are still inconclusive and require further study. The inconsistency in the results point to the need for cross-calibration between different sensors and datasets, if are to be used in combination.

6. ACKNOWLEDGEMENTS

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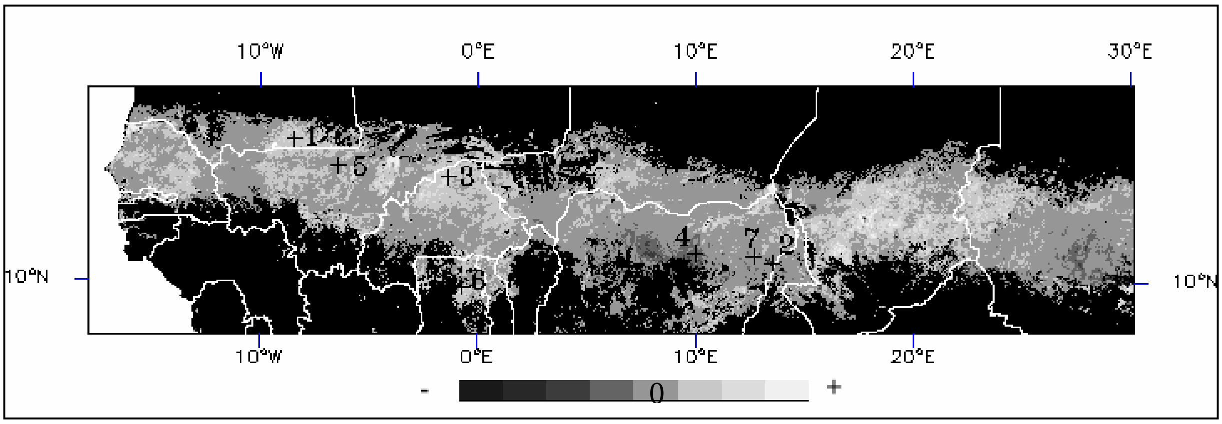

Figure 1. Overall trends in the residual NDVI time series throughout the period 1982 to 2003, based on regression of vegetation greenness (AVHRR NDVI) on three-monthly cumulative rainfall (GPCP estimate). The seven selected locations for which time series were extracted are indicated with +. Definition of the Sahel region is based on a 20-year NDVI average of 0.15 to 0.4.

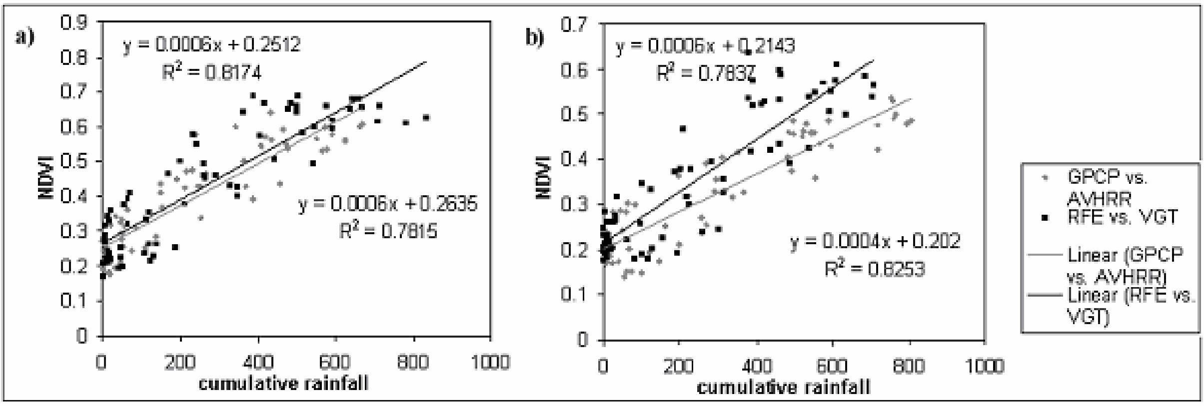

Figure 3. Linear regressions between GPCP rainfall and AVHRR NDVI in comparison with linear regressions between RFE rainfall and VGT NDVI for locations #2 (a) and #4 (b).