Analysing vegetation changes in the Sahel using sensor data from Landsat and NOAA

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Abstract – The semi-arid Sahel zone of Africa has suffered several periods of severe drought since about 1950. We have analyzed AVHRR Normalized Difference Vegetation Index (NDVI) over the Sahel for the period 1982-2002, and found extensive areas of increasing NDVI. To verify these changes we have analyzed Landsat TM and ETM+ scenes from 1984-1986 and 1999-2001 for areas in the Sudan, Central African Republic, Niger, Mali and Mauritania. Changes in the Landsat data were analysed by visual interpretation and change vector analysis. In areas of positive AVHRR NDVI change the analysis of Landsat data generally showed a transition from barren or sparse vegetation to a denser vegetation cover. Rainfall had increased over the course of time in several of these areas. In some areas visual interpretation indicated an expansion of agricultural land.

Keywords: vegetation change, Sahel, Africa, NOAA NDVI, Landsat, change vector analysis

1. INTRODUCTION

The on-going discussion about desertification has great implications on environmental policy in semi-arid lands, especially in the Sahelian region of Africa, a region generally perceived as undergoing environmental degradation. The persistent crisis of drought that began in the early 1970's became a trigger for the surge of interest concerning desertification in the Sahel and precipitated an unprecedented mobilization of resources and a major scientific debate (Rayanaut, 2001). The term desertification is commonly used when active processes such as deforestation, soil erosion, soil nutrient depletion etc., are organized (Rasmussen et al. 2001) and the latest definition on desertification, adopted by the United Nations in the beginning of the 1990s, can be read as: "*Land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities"* (UN, 1992).

Recently, Pathfinder Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) 10-day maximum value composites (MVCs) were analyzed for the African Sahel to investigate trends in vegetation greenness (Eklundh & Olsson, 2003). Their observations indicated that the Sahel belt may be undergoing some very rapid environmental changes, as conspicuous patterns of a strong increase in NDVI was observed over large areas for the period 1982-1999. The observed trend could be a result of a recovery from the Sahelian drought years during the mid 1980s as several previous studies have shown a positive relationship between NDVI and rainfall (Prince, 1991; Nicholson & Farrar, 1994).

The purpose of this paper is to verify and explain the changes observed by Eklundh & Olsson (2003) in the Sahelian region of Africa. The following objectives are included; (i) to confirm recent trends in vegetation greenness over the Sahel using a different coarse-resolution satellite-derived data set, the Global Inventory Mapping and Monitoring System (GIMMS) data; (ii) to confirm and explain changes in vegetation by high-resolution satellite-data analysis in specific areas; (iii) to investigate the influence of precipitation on the observed NDVI change.

2. MATERIALS

Images of 15-day NDVI data at an 8 by 8 km resolution, from the AVHRR flown on the NOAA-series satellites were acquired from GIMMS for the Sahel area for the period 1981-2003. Preprocessing of this dataset involves corrections for sensor degradation, corrections for artifacts in NDVI due to satellite drift and corrections for stratospheric volcanic aerosols from volcanic eruptions in 1982 and 1991 (Slayback et al., 2003). Maximum NDVI was used as a compositing technique with cloud screening based on AVHRR channel 5 thermal threshold values. This reduces the effects of atmospheric aerosols, high scan angles, higher solar zenith angles and residual cloud contamination (Holben, 1986).

A set of 4 pairs of Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) geometrically corrected scenes at 30 by 30 m resolution were acquired for change detection analysis. The specific geographic locations of the areas are as follows: lat. 11°34'N, long. 32°8'E for the Sudan, lat. 7º14'N, long. 21º55'E for the Central African Republic, lat. 14º27'N, long. 6º30'E for Niger, and, lat. 15º54'N, long. 10º11'W for Mauritania. The data have undergone systematic radiometric and geometric correction using standard methods. All images were corrected for sensor differences and subsequently normalized for differences in illumination properties by recalculating pixels into at-satellite reflectance (Markham & Barker, 1986).

Rainfall data was extracted from the Global Historical Climatology Network for the closest meteorological stations to the Landsat scenes.

3. METHODS

Annual time series of NDVI were created for the Sahel (6°-20°N lat.), using the GIMMS AVHRR dataset and the TIMESAT processing scheme (Jönsson & Eklundh, 2002, 2004). TIMESAT fits smooth functions to time-series of

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remotely sensed data, and generates several attributes characterizing the dynamics of vegetation. Two such attributes, the annual amplitude and the annual integrated values, were extracted for each pixel and year. The trends over the 1982-2002 period for these attributes were then computed for every 8 x 8 km grid cell using least-squares regression. Non-significant change was labelled "weak" and significant change was labelled "strong", based on the T-value of the slope coefficient and a 5 % rejection level.

Within the acquired TM and ETM+ imagery, subsets were extracted for change detection analysis. These are all within areas showing no or positive trend in the integrated NDVI images. The change detection of the Landsat TM and ETM+ subsets involved two methods: visual interpretation and change vector analysis.

Change vector analysis is a method for assessing spatial patterns of change that has been applied and advanced since its application by Malila (1980) to characterize change magnitude and direction in spectral space from a first to a second date. Whereas the visual analysis was based on subjective image interpretation the change vector analysis was founded on an at-satellite reflectance based tasseled cap transformation (Huang et al., 2002). Through this technique the direction and magnitude of change was determined.

In order to compare the phenological differences between the TM and ETM+ images the high-resolution data were located in the seasonal vegetation cycle as observed with the NOAA NDVI data (Runnström, 2000). Areas were extracted in the TM and ETM+ datasets corresponding to the 8 by 8 km NOAA pixels, and the NDVI was calculated.

4. RESULTS

4.1 Trend analysis

Changes in seasonal amplitude and seasonally integrated NDVI 1982-2002 are shown in Figure 1. Positive changes cover larger areas in the integrated NDVI change image than in the amplitude change image. Increases in amplitude are generally restricted to a narrow belt in the central Sahel while increases in integral stretch further south. One is also able to discern a belt of strong negative change in amplitude, stretching from east to west, south of the Sahel. These areas appear more scattered and are generally restricted to the southwestern part of the defined area in the integrated NDVI image. Area statistics are summarized in Table 1.

Table 1. PERCENTAGE OF AREAS IN DIFFERENT CHANGE CLASSES 1982-2002, EXCLUDING PIXELS WITH MISSING DATA.

Variable	Weak negative	Strong negative	Weak positive	Strong positive
Amplitude	33%	16%	42%	9%
Integrated value	28%	7%	51%	14%

4.2 Visual analysis

Results from the visual analysis of the Landsat TM and ETM+ images show extensive differences in land cover over study areas in the Sudan and Mauritania as these sites appeared severely desiccated in 1984 as compared to 1999 (an example is given in Figure 2). A transition from generally barren or sparse herbaceous vegetation to more dense vegetation was evident, as well as regeneration of vegetation due to fires. At these sites, the observations indicated an improvement of vegetation cover over the 21-year period.

In the case of the Central African Republic, located in the area of negative change, vegetation between the years did not differ as much, except for a belt around the tributaries of a river running through the scene. It was observed that small forest areas within this site had disappeared. This could be due either to wood extraction for domestic use, or to land clearance for extension of agricultural land around the riverbank.

4.3 Change vector analysis

Results derived from the change vector analysis showed that areas which indicated an improvement in vegetation cover, observed through the visual analysis, also had a large number of pixels with phase angles in a positive greenness direction, thus, supporting the results derived from the GIMMS trend analysis and visual interpretation. Moreover, sites with a strong positive trend in NDVI showed signs of having larger

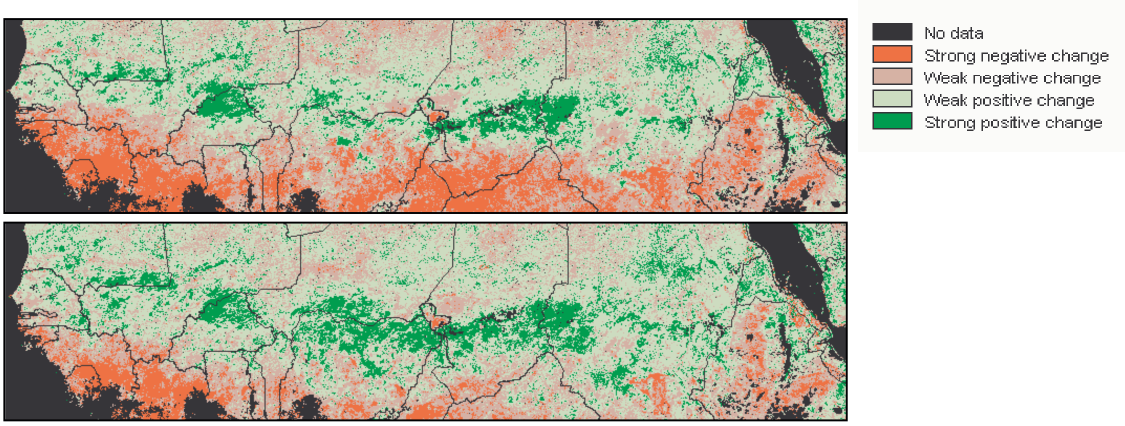

Figure 1. Trend in amplitude NDVI (top) and integrated NDVI (bottom) in the Sahel (between 6 and 20 degrees latitude north) over the period 1982-2002.

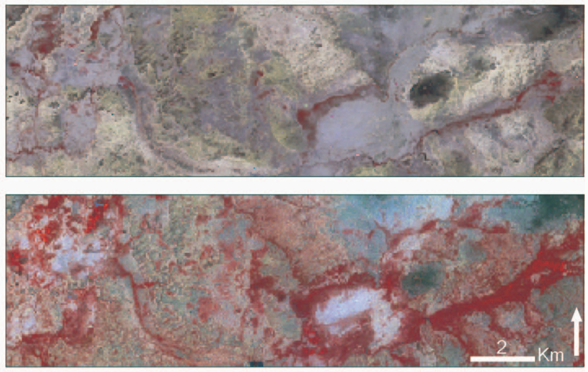

Figure 2. Landsat TM from 1984 (top) and ETM+ from 1999 (bottom) over part of the Mauritania study site.

areas with increased greenness compared to sites without significant NDVI increase. The results of the change vector analysis also revealed some interesting patterns at the Niger study site, where a large number of pixels had phase angles in a positive greenness direction located in agricultural fields.

4.4 Rainfall trends

Trend analysis showed that rainfall had increased over the time period for stations in the vicinity of study sites with strong positive NDVI change, which may suggest a positive link between rainfall and NDVI trends. An example from the Sudan is given in Figure 3. However, annual rainfall for these stations was generally significantly but only weakly correlated to annual NDVI.

4.5 Image comparability

Monthly mean intervals of GIMMS NDVI images were used for comparison with the Landsat TM and ETM+ images and results showed that phenological differences between high-resolution satellite imagery existed, most likely due to different climatic conditions preceding the recordings of the imagery. For sites in the Sudan and Mauritania, the diurnal rainfall pattern between the two years was different, as these areas received significantly more rainfall during 1999 than in 1984. The images generally fit well with the NOAA NDVI, but the difference between the images due to different climatic conditions that preceded the recording of the imagery is evident.

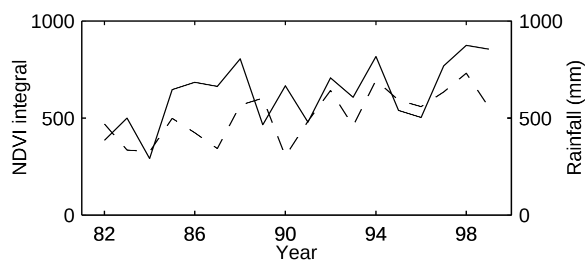

Figure 3. Annual values of integrated NDVI (solid line) and rainfall (dashed line) for an area in the Sudan ETM image.

5. DISCUSSION

Known inaccuracies of AVHRR sensor data arise from coarse resolution, lack of onboard calibration capability for the visible and near infrared channels, and wide spectral bandwidths. Satellite orbital drift may affect trend analyses of the data since the times series is composed of data from four satellites, NOAA-7, -9, -11 and –14. However, Slayback et al. (2003) reported no trends for mid and high latitudes for individual satellites or across the time period for the GIMMS data set, indicating the success of calibration and intercalibration between data from the NOAA satellites. On the other hand, they noted decreasing trends for individual satellites at low latitudes, particularly lat. 5-15º, but also lat. 15-25º, and concluded that these changes do not reflect changes in land surface or atmosphere, but in viewing or illumination conditions. Negative changes in NDVI were always correlated with increasing solar zenith angles (SZA). In a recent study of the trend in Pathfinder NDVI over the Sahel, Lindström et al. (2005) showed only insignificant influence of SZA on the NDVI trend in semi-arid areas of the Sahel, except for data from the year 2000. In moist areas close to the equator their analysis pointed to a possible negative relationship with SZA. Thus, in our study, the impact of changing SZA cannot be ruled out. A weak SZA effect in the semi-arid Sahel would make the estimate of the increasing NDVI trend (green areas in Figure 1) conservative, whereas the stronger SZA effect in humid areas close to the equator would lead to an overestimation of the negative NDVI trend (red areas in Figure 1) in that zone.

The analysis of land-cover change using multitemporal Landsat data is complicated by the presence of substantial radiometric differences (Yuan & Elvidge, 1996; Markham and Barker, 1986). Thus, variations in the radiometric characteristics between TM and ETM+ scenes may exist. However, studies carried out by Vogelmann et al. (2001) show that Landsat 5 and Landsat 7 data have, until 1999, indicated a high degree of similarity, implying that investigations to measure and monitor landscape occurrences can be sustained with minimal caution even if Landsat 7 data are devoid of many of the instrument related artifacts that characterize Landsat 5 data.

The NDVI trend images show a belt of strong increase in the arid to semi-arid zone across the width of the Sahara. The belt is wider in the integrated NDVI image than in the amplitude image. This may be explained by the fact that the amplitude may be affected by saturation of the NDVI at high vegetation densities, whereas the integrated NDVI will reflect also an increase in the length of the growing season. Thus, the integrated NDVI is presumably less sensitive to saturation and a better indicator of vegetation improvement than the amplitude.

In areas of positive NDVI change the visual analysis and the change vector analysis indicated a transition into more densely vegetated land cover classes for the sites located in the Sudan, Niger and Mauritania. Although rainfall had also increased in these areas, the weak interannual correlation between rainfall and NDVI indicates that there may also be other explanatory factors affecting the trend in NDVI.

Some plausible contributing explanations should be mentioned. One explanation could be improved land management or differences in the amount of agricultural fields cultivated. For instance, the Niger study area contained a large number of fields that, according to the change vector analysis, had undergone a vegetation increase. In a survey of 136 farm households located in southern and central Niger, most farmers mentioned that the proportion of cultivated fields to fallow fields had increased from the mid 1980s to the present time (Wezel & Haigis, 2002). However, it is premature to conclude that all crop areas show higher greenness or NDVI than fields that are left fallow (depending on density, type of crop and temporal growing pattern).

A second explanation for the increased greenness could be a change in vegetation type, as it has been shown that species show inter-annual fluctuations in their occurrence in the Sahel (Wezel & Schlecht, 2004). An increasing NDVI trend, thus, may not only be due to an increase in vegetation productivity, but also to a change in annual and perennial species composition.

Numerous other factors that may influence vegetation density, such as migration, and thereby changes in land pressure, may contribute to a possible explanation of the strong trends observed in NDVI in the semi-arid Sahelian zone. Since the influence of the different various explanatory factors is so far based mainly on speculations it is clear that further inter-disciplinary research is needed.

6. CONCLUSION

Large areas in the arid and semi-arid zone of African Sahel, previously affected by severe drought, show a strong increase in AVHRR NDVI over the time period 1982-2002. A number of sites within these areas were further studied by visual interpretation and change vector analysis of Landsat TM and ETM scenes from 1984-86 and 1999-2001 respectively. The derived results support a conclusion that areas with a strong positive trend in AVHRR NDVI are greening. However, causes behind this greening are difficult to ascertain, as results show that increasing rainfall does not fully explain the observed trends.

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