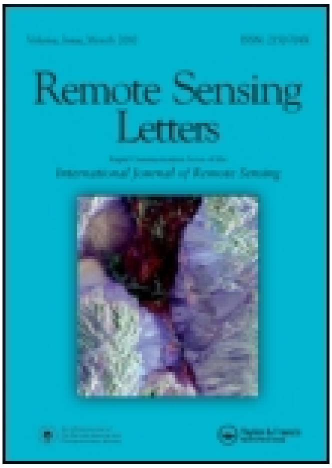

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The influence of seasonal rainfall upon Sahel vegetation

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Throughout the Sahelian region of Africa, vegetation growth displays substantial inter-annual variation, causing widespread concern in the region as rain-fed agriculture and pastoralism are a means of sustenance for the predominantly rural population. Previously proposed factors behind variations include changes in total yearly rainfall, land-use change and migration. But these factors are not fully explanatory. This study addresses other possible factors for variation in vegetation patterns through the analysis of the Normalized Difference Vegetation Index (NDVI) produced by satellite sensors. We focus on precipitation, but instead of looking at the total yearly amount of rainfall, the intra-annual variation is examined. Here we show that plant growth is strongly correlated with the number and frequency of days within the rainy season upon which there is no rainfall. Furthermore, we find that if the start of the growing season, or the period in which the peak growth of vegetation occurs, is especially dry then plant growth may be stunted throughout the remainder of the season. These results enable better understanding of climate dynamics in the Sahel and allow more accurate forecasting of crop yields, carbon storage and landscape changes without the need to resort to rainfall estimates that are sometimes of low accuracy. In addition, it may be possible to apply the results to other dry land regions worldwide.

1. Introduction

The Sahelian climate is characterized by a long dry season and a short humid season in the summer, with increasing scarcity and variability in rainfall from South to North (Herrmann *et al.* 2005). The spatial and temporal variability in precipitation in the Sahel is a major challenge for local livelihoods (Dietz *et al.* 2004). The vegetation of the Sahel primarily consists of bushes, grasses, scattered trees and crops. The ecosystem can be characterized as dynamic, responding to climate fluctuations, but changes in vegetation patterns cannot be explained by a single factor such as total annual rainfall (Nicholson 2000, Olsson *et al.* 2005). This letter seeks to analyse variation in the growth of vegetation by focusing on several features of intra-annual rainfall variation that were postulated by those living in the Sahel as having a key influence upon vegetation development. Five years of satellite data were used in the examination of these influences by a comparison of rainfall data to the Normalized Difference Vegetation Index (NDVI) (Tucker 1979) that is frequently used in examining vegetated landscapes. Many studies of the Sahel have been conducted with such data and have shown, among other things, the effects of climate change upon the Sahel (Zeng *et al.* 1999, Eklundh and Olsson 2003, Anyamba and Tucker 2005, Herrmann *et al.*

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2005), the evolution of land cover, both from man-made and from natural factors (Nicholson *et al.* 1998, Symeonakis and Drake 2004, Heumann *et al.* 2007) and the yield of various crops (Maselli *et al.* 1992, Rasmussen 1992, Groten 1993). By performing field work in one area of the Sahel, a number of theories that relate the temporal distribution of rainfall to the growth of crops were uncovered. Satellite data for both rainfall and NDVI were then used to test the validity of these theories for the original field study area and for the West African Sahel as a whole.

2. Methodology

2.1. *Field work*

Field work was carried out in two provinces (Oudalan and Seno) of northern Burkina Faso in February, 2010. Interviews with agricultural authorities from the two provinces were conducted with the aim of identifying the main constraints or advantages for agricultural productivity in the study area when related to the intra-annual distribution of precipitation. Furthermore, a total of 23 interviews with randomly selected farmers were carried out in three villages to provide the basis for a characterization of farmers' perceptions of constraints and advantages for agricultural productivity. Farmers were asked to mention key factors in relation to rainfall influencing vegetation development.

By interviewing these farmers, three factors relating the variation in rainfall to the growth of crops were postulated. First, farmers were concerned about dry periods within the rainy season, which agrees with literature stating that short periods of water stress may have serious impacts on crop yields if occurring during water-sensitive stages such as flowering (Rockstroem and De Rouw 1997). They reported that the more unevenly rainfall is distributed throughout the growing season, the lower the crop growth. The second factor mentioned by farmers was the timing of dry periods within the rainy season. If a significant number of dry-days occurs shortly after the start of the rainy season then a 'false rainy season' is said to exist. There was an agreement that a long dry spell early in the growing season had a detrimental impact upon plant growth. The third factor farmers mentioned as essential for crop growth was sufficient rainfall in August. Rainfall towards the end of the rainy season is an important determinant of the amount of water available during the periods when vegetation matures (Dennett *et al.* 1981) and this may have an influence on the NDVI data as the maximum yearly NDVI has been shown to be linked to the yield of crops (Maselli *et al.* 2000) and hence the maturation of many types of vegetation.

To determine the importance of these factors, each was tested by examination of the NDVI and rainfall data across the Sahel.

2.2. *Satellite data*

To examine the trends in vegetation growth, the NDVI derived from data produced by the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) aboard the Meteostat Second Generation (MSG) satellites was used (Aminou 2002). SEVIRI provides the capability to acquire data in almost real time, with one observation every 15 minutes in the visible and near-infrared wavelengths. The raw SEVIRI data were atmospherically corrected using an upgraded version of the simplified method for atmospheric correction (Rahman and Dedeiu 1994), and surface anisotropy was minimized by a modified version of the MODerate Resolution Imaging Spectroradiometer (MODIS) Bidirectional Reflectance Distribution Function (BRDF) method (Strahler *et al.*

1999, Schaaf *et al.* 2002) that produces Normalized BRDF Adjusted Reflectances (NBARs) that are normalized to a common scene geometry. Both these methods are well validated and result in high-quality land surface reflectances (Salomon *et al.* 2006, Proud *et al.* 2010). An accuracy assessment of the NBARs was performed which showed that the SEVIRI data were accurate to within ±10% compared to the data from other satellite sensors. This assessment also showed that the SEVIRI NBARs were resistant to cloud contamination. Each month was divided into three dekads (days 1–10, 11–20 and 20–end of month) to provide the BRDF method with a suitably large selection of input reflectances to model while simultaneously allowing a short enough acquisition time to enable short-term land surface changes to be visible within the NBAR. The final NBARs are converted into NDVI values, and these can then be used for the analysis of vegetation trends. As a final step, a land-/water mask (derived from the EUMETSAT cloudmask) was applied. This removed water bodies from the data, as such areas would substantially bias the results of the study.

Also used is rainfall data on daily, monthly and seasonal timescales. This has been derived from the Tropical Rainfall Monitoring Mission (TRMM) satellite rainfall estimates (Kummerow *et al.* 1998) and is coarser than the MSG data with a 28-km resolution but was chosen because of its spatial coverage. *In situ* data are available but sparse, covering small regions around each measurement station, and are hard to extrapolate into a data series covering the entire extent of the Sahel. The TRMM data contain an uncertainty in the rainfall estimate, typically of less than 24% (Kummerow *et al.* 2000), and cannot usually detect daily rainfall amounts of less than 0.5 mm (Kawanishi *et al.* 2000).

The TRMM data were downloaded on both 3-hour and monthly timescales that specify an average hourly rainfall rate (mm $hour^{-1}$). The monthly data were used for validation whereas the 3-hour data were combined to produce a daily rainfall estimate. All pixels in the study region that experienced more than 2 mm of rainfall within 1 day were then extracted and the remaining pixels were classified as dry, and were included in a count of the total dry pixels. The total rainfall within the season was calculated by summing the rainfall between the start and end dates of the rainy season in each year, which were also used to compute the maximum and mean seasonal NDVI from the SEVIRI data. These dates were computed by the TIMESAT software (Jonsson and Eklundh 2002, Jonsson and Eklundh 2004). TIMESAT can examine a multi-year time series of remotely sensed dataset – rainfall in this case – and attempts to fit a curve to the data on a seasonal basis. This curve fitting enables detailed analysis of seasonal trends (e.g. Eklundh and Olsson 2003, Heumann *et al.* 2007), including the season start and end dates that are used within this study. These start and end dates vary between individual pixels across the Sahel, but the start date usually occurred after around 10% of the total yearly precipitation had fallen and the end date occurred when the rainfall exceeded 92% of the yearly total.

The total number of dry-days and the number of dry-days in each month were found through a simple summation. The number of dry-days near the start of the rainy season (the false rainy season, see section 3.3) was also computed. After using TIMESAT to find the start of the season, each subsequent day was cycled through, with dry-days being summed until a day with more than 2 mm of rainfall was found. Initially, this study was confined to the region of Burkina Faso in which field work was carried out (see section 2.1), but this was broadened to include the whole of the West African Sahel, which is often defined climatically as the region between the 200- and 800-mm isohyets, covering an area from 18°W, 18°N to 9°E, 12°N.

3. Results

3.1. *NDVI and rainfall trends*

Between 2005 and 2009, the average NDVI for the rainy season throughout the Sahel has fallen slightly, with a mean annual decrease of 0.45%. Mauritania and Western Mali experienced an increase in NDVI of 2–6% annually, however. There have been significant decreases to the East of the Inner Niger Delta, with northern Burkina Faso showing a drop of 5% per year and Niger a drop of 1–4%. Small areas of the Eastern Sahel show increases, but these appear concentrated in well-irrigated areas, such as the banks of the Niger and Sokoto rivers. The maximum annual NDVI shows average decreases of 0.76% per year over the region. Following a similar pattern to the mean NDVI, areas showing the largest changes over the 5-year period are in the East, with typical decreases of between 5 and 9% per year. The West, including Mauritania and Mali, show increases of between 4 and 6%.

Annual rainfall shows no trend in the past 5 years across the Sahel as a whole, with increases in some areas and decreases in others. But a link exists between changes in annual rainfall and NDVI. Of the pixels that display a significant trend ($p < 0.01$) in NDVI and rainfall, 33.8% show a decrease in both, 8.3% show a decrease in rainfall but an increase in NDVI, 22.6% exhibit a decrease in NDVI but an increase in rainfall and 35.3% show an increase in both. The majority of pixels where rainfall and NDVI have increased are in Mauritania, although areas in the Eastern Sahel exhibit a decrease in both variables, as shown in figure 1. The correlation of mean and maximum seasonal NDVI to rainfall was 0.41 and 0.37, respectively, meaning that it is possible for the variations in rainfall to be responsible for some of the NDVI trends, but that they are unlikely to be the sole variable affecting the NDVI.

This conforms well with the statements by the interviewed farmers, as they stated that the variability in precipitation within the rainy season is of major importance to crop growth.

3.2. *Total length of dry periods*

To examine the effects of the first theory postulated by farmers, the total number of dry-days within the rainy season was calculated for both the interview area and the

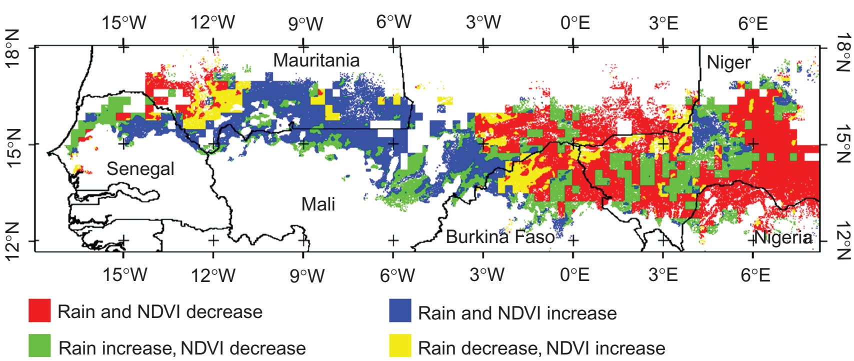

Figure 1. A map of West Africa showing areas with significant rainfall and NDVI trends between 2005 and 2009. White areas were not included in the analysis, either due to no significant trends ($p < 0.05$) or due to regions not being part of the study area.

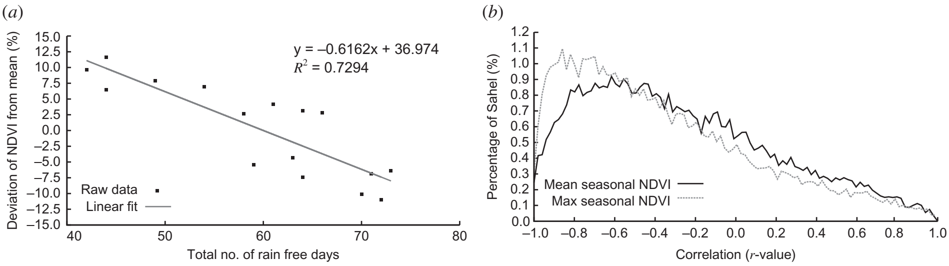

Figure 2. Trends in NDVI and the total number of dry-days present within the rainy season for Burkina Faso and the Sahel. (*a*) shows the relationship in the study region within northern Burkina Faso. (*b*) displays a histogram containing the correlations of maximum and mean seasonal NDVI to the number of dry-days for the Sahel as a whole. The bin size for the histogram is 0.01 correlation units, with 72.7 and 78.5% of pixels having an *r*-value of less than 0 for the mean and maximum NDVI, respectively.

Sahel as a whole. It was found that the total number of dry-days within the rainy season is correlated with both the maximum and mean seasonal NDVI values in many areas. Figure 2(*a*) shows the relationship between dry-days and mean NDVI for the area of Burkina Faso in which the farmer interviews were carried out.

The linear regression reveals that every dry-day may decrease the mean seasonal NDVI by 0.62%, showing that – for this study area – the hypothesis that the number of dry-days has a significant negative effect upon vegetation growth is supported by the satellite data. To test over a wider area, the study was expanded across the whole of the Sahel. The results of this expansion are shown in figure 2(*b*) that displays a histogram of the correlation between dry-days and mean/max NDVI for every pixel within the Sahel. It is clear that even on this scale there is still a link between NDVI and dry-days, with most pixels displaying a negative correlation between the two variables. The mean seasonal NDVI shows an average correlation of –0.25 whereas the correlation is –0.38 for the maximum NDVI. The larger correlation with maximum NDVI indicates that this variable may be more sensitive to variation in rainfall than the mean NDVI. There is, however, a wide spread of values. This is due to a number of possible factors, of which two are postulated to be of particular importance. First, the rainfall data used to determine the number of dry-days are at lower resolution than the NDVI data – so each rainfall pixel will have a range of NDVI pixel values associated with it that will not display an identical response to rainfall variation. However, as the Sahel is relatively homogeneous this should not have a large effect upon the results of the study whereas using SEVIRI data at its native resolution allows for more accurate masking of water bodies. Second, the study region includes areas close to rivers, lakes and irrigated landscapes that are not solely reliant upon rainfall to provide water for plant growth – and these bias the correlation shown in figure 2(*b*) as they are atypical for the Sahel.

3.3. *The false onset of the rainy season*

The false onset of the rainy season was also examined, and figure 3 shows the correlation between the length of the first dry period to the yearly NDVI values for the whole Sahel. It shows that a false start to the rainy season is indeed correlated with plant growth, with the majority of Sahelian pixels showing a negative correlation to

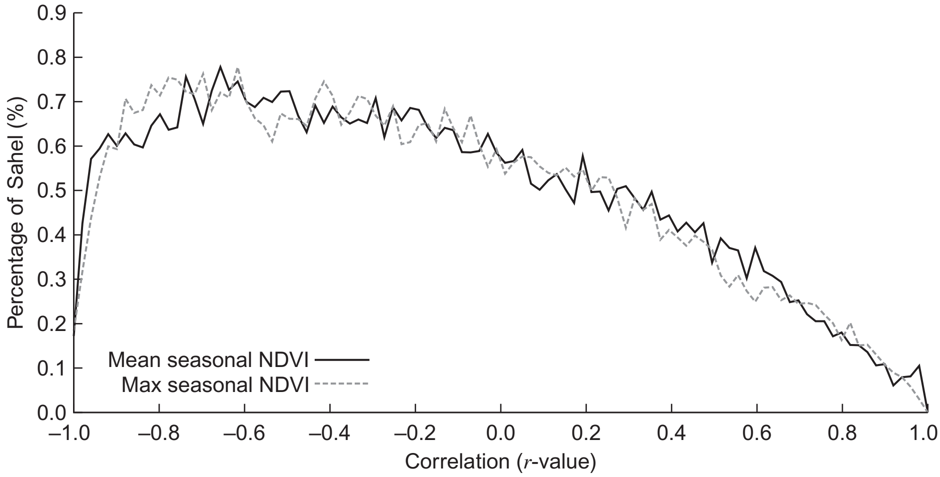

Figure 3. A histogram showing the correlation of average (solid) and maximum (dashed) seasonal NDVI with the length of the first dry period after the start of the rainy season. The bin size for the histogram is 0.01 correlation units, with 65.4 and 64.8% of pixels having an *r*-value of less than 0 for the mean and maximum NDVI, respectively.

initial dry period length. The mean and maximum seasonal NDVI produce average correlation coefficients across the Sahel of –0.16 and –0.2, respectively, and although not as strong as the link to the total number of dry-days, this correlation is still statistically significant ($p < 0.05$). This is substantially affected by the regions of irrigation as in those areas there is a positive correlation with the length of the dry spell – most likely due to stored water being used to irrigate the land whereas the clear – rain free – skies provide ample sunshine to stimulate plant growth. Additionally, the MODIS land–cover product (Friedl *et al.* 2002) was used to determine land–cover type, and it was found that the land type also has an effect upon the growth trends, with grassland and shrubland showing a larger negative correlation than cropland. Substantial parts of Burkina Faso, Mali and Mauritania all show large negative correlations of between –0.6 and –0.9, meaning that far from water sources the false onset of the rainy season is well correlated with NDVI. This indicates that the false onset of the rainy season may have an impact upon the growth of vegetation throughout the remainder of the year in these regions.

3.4. *Lack of rainfall within the month of August*

The final factor postulated by farmers was that a lack of rain near the peak in crop growth resulted in a more pronounced drop in crop productivity than would be expected due to a lack of rain at any other time in the growing season. When examining the Burkina Faso/West Niger region, this appears to be partially supported by a correlation analysis. Figure 4(*a*) shows the partial correlation between the number of dry-days in August and July with the mean NDVI. By examining the partial correlation, we remove much of the effects caused by the two factors discussed in sections 3.2 and 3.3. For August there is a mean correlation of –0.16, indicating that increased numbers of dry-days in this month may reduce the mean seasonal NDVI over and above which is expected from the effect of the total number of dry-days. For

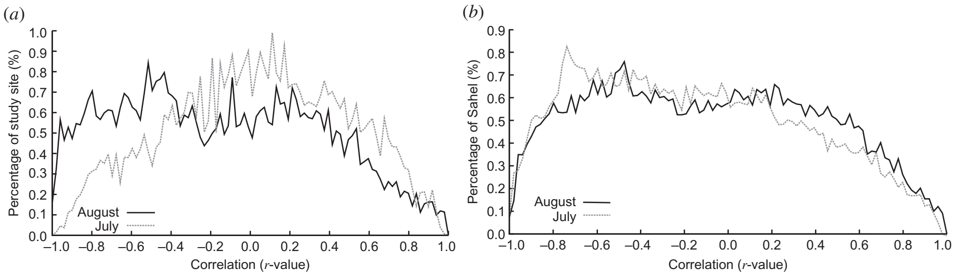

Figure 4. Trends in NDVI compared to dry-days in July and August. The bin size for both histograms is 0.01 correlation units. (*a*) shows a histogram only for the Burkina Faso study area, with 45.5 and 59.0% of pixels having an *r*-value of less than 0 in July and August, respectively. (*b*) shows a similar histogram for the whole of the Sahelian study region, and in this case 61.4 and 55.7% of pixels have *r*-values of less than 0 for July and August, respectively.

July this is not true, as the mean correlation is 0.02, meaning that the number of dry-days in July is unlikely to be of greater influence upon the seasonal NDVI than is expected from the dry-day analysis shown in section 3.2, something that is true for all months of the year other than August. There are substantial variations in this pattern, though, with some areas showing negative trends for both months, and some showing positive trends for 1 month. Examination showed that the strength of the relationship is dependent on the start date of the rainy season. Negative correlations in July imply an earlier rainy season start and negative correlations in August are visible where the rainy season started later. Therefore, it is likely that the effect being observed is not specific to August, but rather related to the length of time since the start of the season. This is supported when examining the whole of the Sahel, as shown in figure 4(*b*), where it appears that July is slightly more influential upon the NDVI values than August. Only Burkina Faso and Niger show a strong correlation with August. Regions where only July shows a strong negative correlation have a rainy season start date on average 18 days earlier than that for areas in which August is more influential.

4. Conclusions

We have shown that three intra-annual precipitation factors have a statistically significant correlation ($p<0.05$) with the growth of vegetation: the total number of dry-days within the rainy season, the length of any false rainy season start that may occur and the number of dry-days that occur near the peak of the rainy season, typically in July or August. By combining these factors, it may be possible to estimate the effects of precipitation changes upon the Sahel without the need to examine the – frequently uncertain – rainfall amount. It may be possible to use the correlations discussed in this study, particularly the false rainy season start, to partially predict future growth trends within a season, something of great use in determining famine possibilities as well as investigating the carbon dioxide storage potential of the Sahel. The results may also be applicable to other regions worldwide in which rainfall is the primary influence upon plant growth.

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