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Many studies have shown a 'greening of the Sahel' on the basis of analysis of time series of satellite images and this has shown to be, at least partly, explained by changes in rainfall. In northern Burkina Faso, an area stands out as anomalous in such analysis, since it is characterized by a distinct spatial pattern and strongly dominated by negative trends in Normalized Difference Vegetation Index (NDVI). The aim of the paper is to explain this distinct pattern. When studied over the period 2000–2012, using NDVI data from the MODIS sensor the spatial pattern of NDVI trends indicates that non-climatic factors are involved. By relating NDVI trends to landscape elements and land use change we demonstrate that NDVI trends in the north-western parts of the study area are mostly related to landscape elements, while this is not the case in the south-eastern parts, where rapidly changing land use, including. expansion of irrigation, plays a major role. It is inferred that a process of increased redistribution of fine soil material, water and vegetation from plateaus and slopes to valleys, possibly related to higher grazing pressure, may provide an explanation of the observed pattern of NDVI trends. Further work will focus on testing this hypothesis.

Keywords: Sahel; greening; land degradation; NDVI; spatial patterns

1. Introduction

Since the drought in the 1970s and 1980s it has been debated whether desertification – or the reverse – could be attributed to climatic or human factors (Geist, 2005; Geist & Lambin, 2004; Huber et al., 2011; Rasmussen et al., 2001). Several studies have demonstrated that Sahel, as a whole, has been characterized by a positive trend in 'vegetation greenness' (as represented by Normalized Difference Vegetation Index [NDVI] measured from satellite) over the period 1981 to date for which a homogeneous time series of satellite data is available (Anyamba & Tucker, 2005; Fensholt et al., 2012, 2006; Fensholt & Rasmussen, 2011; Olsson et al., 2005; Seaquist et al., 2009, 2006). The output from such an analysis, based on the National Oceanic and Atmospheric Administration, Advanced Very High Resolution Radiometer, Global Inventory Modeling and Mapping Studies (NOAA, AVHRR, GIMMS)3G data-set, is shown in Figure 1 (a). A detailed technical description of the analysis illustrated in Figure 1 is given in Section 3.1. It has been shown that much of the variation in annually or seasonally summed NDVI (ΣNDVI) may be explained by rainfall (Fensholt et al., 2013; Herrmann et al., 2005; Hickler, Eklundh et al., 2005; Huber et al., 2011).

However, with the availability of time series of higher spatial resolution data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on-board the Terra satellite, now covering 13 years, it is evident that certain parts of the Sahel display trends which, judging from the spatial pattern, are unlikely to be attributable to climatic factors alone. One such case can be observed for the period 2000–2012 in parts of northern Burkina Faso, more specifically in an area close to Aribinda located in the Soum Province. In Figure 1 (b) and (c) maps of trends in NDVI, derived from both the above-mentioned GIMMS data-set and time series of MODIS data have been shown for the selected study area. ΣNDVI may be considered a proxy for vegetation productivity, and thus trends in ΣNDVI might be used as an indicator (among several) of land degradation (and the reverse), as defined by United Nations Convention to Combat Desertification (UNCCD). It is evident from Figure 1 that positive trends dominate the Sahel-Sudan as a whole, as well as Burkina Faso in general for the 1982–2011 period (GIMMS3g data). It has been shown (Fensholt et al., 2009) that, generally speaking, MODIS and GIMMS data produce similar NDVI trends, yet MODIS is better calibrated and provides the most robust estimates of trends. Figure 1(b) and (c) further shows that negative trends dominate the case study area for the 2000–2012 period. When observed in the spatial resolution of MODIS data (250 m), the spatial pattern of trends in the study area is very distinct, and cannot be seen in the GIMMS 3G NDVI time-series from NOAA AVHRR, due to its coarser spatial resolution (1/12° ≈ 9 km).

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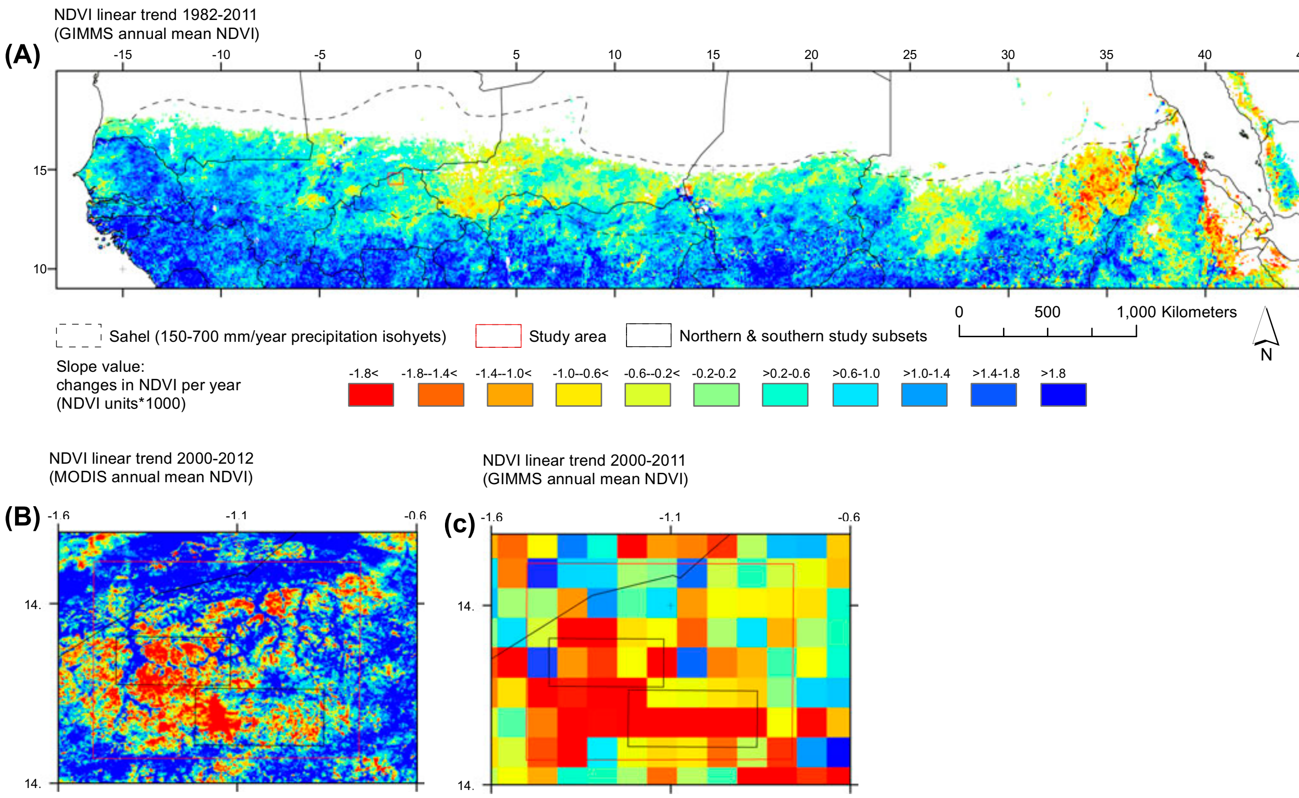

Figure 1. (a) GIMMS NDVI linear trend (1982–2011) for the Sahel. Only trends for areas of annual NDVI std. dev. > 0.02 are shown. (b) MODIS NDVI linear trend (2000–2012) for study area. (c) GIMMS NDVI linear trend (2000–2011) for study area.

The predominance of negative trends, as well as the very distinct spatial pattern observed in the study area, was the basis for its selection. As mentioned, it differs significantly from other parts of northern Burkina in terms of terrain and, therefore, it should not be considered representative for a wider region. Other areas in the Sahel with similar patterns may be found, however.

The main objective of this study is to identify possible explanations of the observed distinct pattern of trends in the period 2000–2012 for the study area, and specifically which processes, natural or anthropogenic, have been in play.

It should be noted that many processes causing changes in ΣNDVI may not be expected to result in linear trends in ΣNDVI. However, since this study focuses on the short time-span from 2000 to 2012, detection and explanation of non-linear components of change will not be robust.

Analysis of very high resolution (VHR) data shows that the south-eastern part of the study area, around the village Kekenene, has relatively high population density and many fields. A dam was built around 2007, causing population increase and expansion of both irrigated and rain-fed farming. The northern and western parts have much lower population density, and are mainly used for livestock grazing and fuelwood collection. As evident from Figure 1 (b), both areas (study subsets) have negative average trends.

2. Two explanatory models of the pattern of NDVI trends in the case area

Many mechanisms of land degradation (and the reverse) have been suggested (Mortimore & Turner, 2005; Reynolds & Stafford Smith, 2002; Reynolds et al., 2007). Generally speaking, these mechanisms may be classified in two main categories, one related to climate change, either 'natural' or caused by human-induced increases in greenhouse gas concentrations, and one associated with local human impact, mostly related to human-induced land use change (Schellnhuber et al., 1997), such as expansion of cultivation, agricultural intensification, overgrazing and overuse of woody vegetation (Le Houérou, 2002). Many studies combine mechanisms from the two categories. Each of these suggested causal mechanisms may be expected to result in a characteristic spatial pattern of degradation. The climatic mechanisms may include effects of changes in rainfall, both amount, temporal distribution and intensity, as well as in air temperature. With specific reference to the study area, it is worth noting that cultivated land covers only few per cent of the area, mostly concentrated in the southern part and in the valleys. The greater part of the land area, especially in the north and west, is used for grazing of livestock, some of which belongs to sedentary agro-pastoralists, others to transhumant pastoralists.

It is particularly noteworthy that the spatial pattern of ΣNDVI trends observed in Figure 1 (b) appears to be associated with topography and/or geomorphology. However, it is not evident that a trend in greenness/vegetation productivity can be explained by a static variable, such as topography or geomorphology, yet it suggests that some process depending on topography or geomorphology is in play. This study aims at investigating what this process might be.

Two explanatory models, relating to the two parts of the study areas shown in Figure 1 (b) and (c), may be suggested as explanations of the observed patterns:

Model 1: extensive changes in land use/cover, associated with the expansion of cultivation, rain-fed as well as irrigated, especially in the valley bottoms, have led to both positive and negative ΣNDVI trends: establishment of the dam and reservoir itself has caused a negative trend, while expansion of irrigated fields may be assumed to have caused positive trends. Expansion of rain-fed agriculture may have given rise to both increase and decrease in ΣNDVI, depending on the greenness of the natural vegetation being displaced. On the hill-sides and plateaus, the ΣNDVI trends are affected negatively by expanding areas of human habitation and by locally increased grazing/browsing pressure. The resulting pattern of ΣNDVI trends does not reflect topography very clearly, since valleys experience both increase and decrease, yet is more affected by expansion of habitation and cultivated fields. The increase in population density and cropped area will imply higher grazing pressure, as well as a more intensive collection of wood for fuel and building materials.

Model 2: outside the reach of agricultural expansion, associated with the village of Kekenene and the dam, ΣNDVI trends are affected by landscape-scale redistribution of water, fine soil material and vegetation, associated with increases in grazing pressure and wood collection and/or changes in rainfall patterns. Soil surface crusting, related to increased grazing and reduction in woody cover, and higher rainfall intensity cause run-off to increase, leading to vegetation loss on the plateaus and slopes, as well as increased water availability, accumulation of fine soil material and greater vegetation cover in the valleys. This implies a negative ΣNDVI trend on the plateaus and slopes and a positive ΣNDVI trend in the valleys.

Obviously, the first explanatory model is mostly relevant in the area around Kekenene and the dam, and the second for the northern and western parts of the study area.

3. Data and methodologies

3.1. Data requirements to test the two explanatory models of anomalous NDVI trends

In order to test the validity of the two hypothetical explanatory models, suggested above, data are required on a range of variables:

3.1.1. Vegetation greenness trends

Long-term trend analysis of the MODIS NDVI (MOD13Q1, collection 5) and GIMMS 3G time-series are performed using a Theil–Sen median slope trend analysis, which is a linear trend calculation known to be resistant to the impact of outliers (Hoaglin et al., 2000). This method is related to linear least square regression trend techniques; however, it is based on non-parametric statistics and is particularly effective for the estimation of trends in short and noisy series. MODIS 16-day and GIMMS 3G bi-monthly NDVI composites were summed into annual NDVI values (MODIS ΣNDVI) before calculating the trends. The value of the slope of the line fitted to the NDVI-time series data for each pixel indicates the rate at which the change in greenness has taken place. Slope values represent the total increase/decrease in MODIS ΣNDVI over the period covering 2000–2012.

3.1.2. Changes in land cover

Our main source of information on changes in land cover is visual interpretation of high and VHR satellite images: Worldview from 25 December 2010 and 22 September 2010, with 0.5 m resolution; Landsat ETM from November 1998, October 2006 and September 2009, with 30 m resolution; and aerial photos from 1980. It is evident that consistent identification of land use change is difficult due to the differences in resolution and the time of year of image acquisition.

3.1.3. Landscape elements

In order to relate ΣNDVI trends to landscape elements (valleys vs. slopes and plateaus), a classification of the area has been done on the basis of a visual interpretation of a Landsat ETM image.

3.1.4. Grazing/browsing pressure

Although general statistics on livestock numbers at the regional level suggest an almost exponential increase (Rasmussen et al., 2012), the grazing pressure, at a spatial resolution corresponding to that of the satellite data,

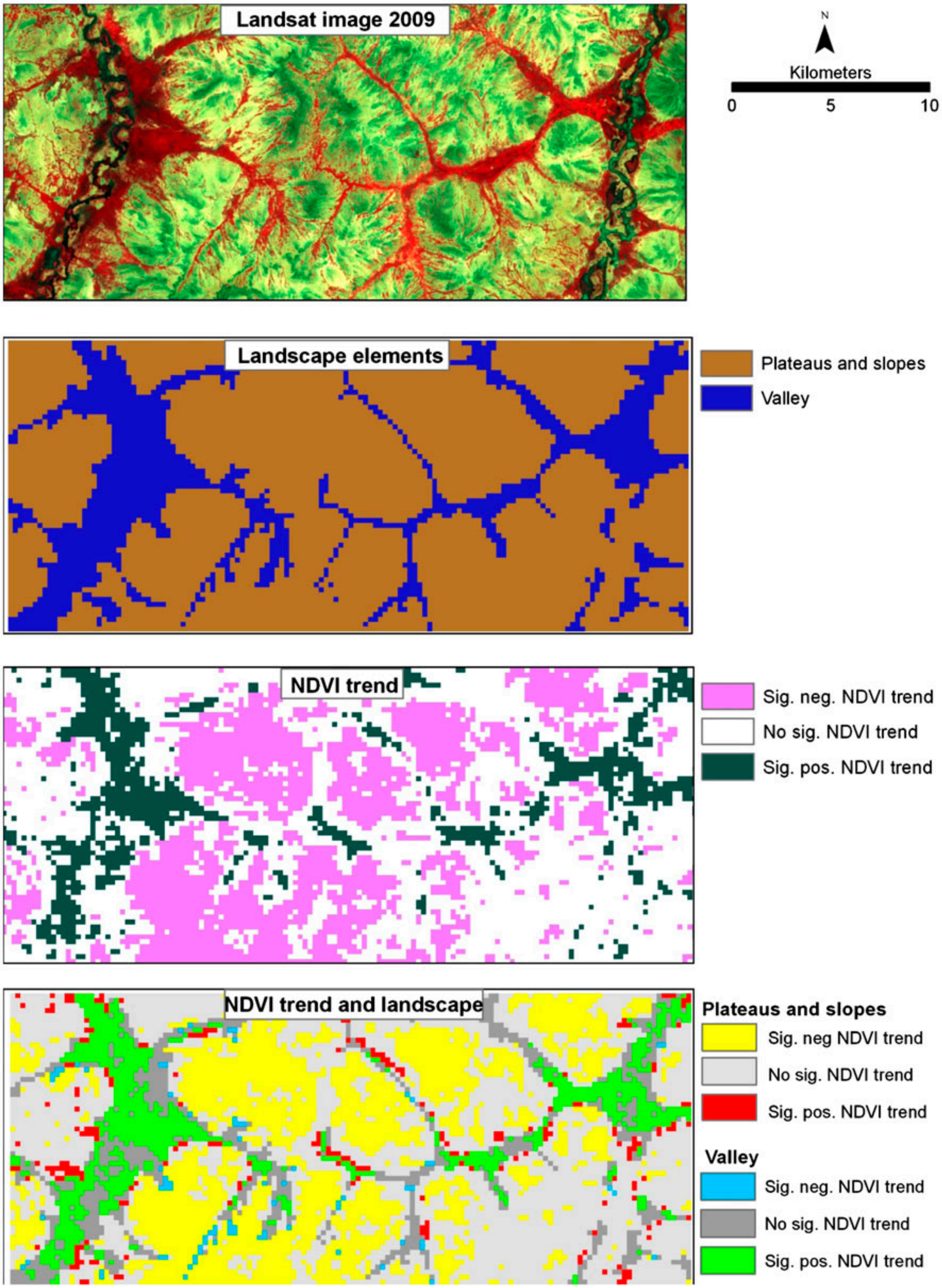

Figure 2. Analysis of ΣNDVI trends from the north-western part of the study area. From top to bottom: a Landsat ETM image from September 2009, depicting the landscape elements in the study area mapped on the basis of the Landsat image, the distribution of significant positive and negative ΣNDVI trends, and the significant ΣNDVI trends overlaid on the landscape elements. The boundary vectors of landscape elements have been converted to raster form and resampled to MODIS resolution (250 m).

is difficult to quantify. This is firstly due to the fact that regional statistics are not necessarily trustworthy as the well-known decrease in livestock population during the 1970s and 1980s is not displayed in the national Burkina Faso data-set. Secondly, the spatial mobility of the livestock implies that regional livestock numbers hardly provide information on grazing pressure at any specific location. In times with depleted fodder resources a southward migration with the animals is, for example, often evoked (Mortimore & Turner, 2005; Powell et al., 1996). In the case area, the inflow of people to the south-eastern part, due to the dam construction, may nevertheless be assumed to have led to an increase in livestock numbers.

3.1.5. Rainfall

Rain gauge data from the study area are not available, and due to the high spatial variability of rainfall rain gauge data from outside the study area they are of little use in the current context. Monthly rainfall data for the relevant grid-cell of the Tropical Rainfall Measuring Mission (TRMM) data (provided on a $0.25° \times 0.25°$ grid) are used instead.

3.2. Testing the two explanation models

The statistical relationship between landscape elements and ΣNDVI trend has been studied using standard non-parametric techniques. As mentioned, no direct causal links between a quasi-static 'variable', such as landscape elements, and a dynamic variable, such as the ΣNDVI trend, are likely to exist, yet if statistical relations are detected, this points towards a causal mechanism involving topography. Both the explanatory models suggested above involve an effect of topography or geomorphology.

4. Results

4.1. Relation between landscape elements, land cover, land cover change and ΣNDVI

In Figure 2 the relationship between landscape elements and ΣNDVI trends (2000–2012) are shown for the north-western part (study subsets shown in Figure 1) of the study area. In Table 1, the distributions of significant positive and negative trends for each landscape element are shown for the north-western part. From Figure 2 and Table 1 it is evident that positive ΣNDVI trends are almost exclusively found in the valleys and negative ΣNDVI trends on the plateaus and slopes.

In the south-eastern part of the study area, near Kekenene and the dam, land use/cover has been impacted by population influx, causing expansion of the village areas and fields. In Figure 3, the results of the same analysis as the one illustrated in Figure 2 (the north-western part) have been shown. The visual interpretation of Worldview images from 2010 shows many habitations in the area, especially on the slopes at the edges of valleys. Many of these habitations cannot be identified in the aerial photos from the 1980s, which are, however, of inferior quality as compared to the Worldview images and acquired during the dry season, making them less useful for identification of fields and houses. The much lower resolution of the Landsat ETM images does not allow for identification either. Thus, it is not possible to quantify the land use change, yet it is clear that many more people live in the area now, as compared to the 1980s, and the extent of farming in the valleys has increased.

Parallel to Table 1, Table 2 shows the distributions of significant positive and negative trends for each landscape element for the south-eastern area. As evident from Figure 3 and Table 2, the south-eastern area differs markedly from the north-western part, since the distributions of positive and negative trends are not clearly related to landscape elements. While valleys have a weak dominance of positive trends, and plateaus and slopes a week dominance of negative trends, larger areas do not display significant trends at all.

4.2. Relation between ΣNDVI and rainfall

Annual rainfall and ΣNDVI values over the period for the study area, as well as the relation between annual rainfall and ΣNDVI, aggregated to the resolution of the TRMM data-set, are shown in Figure 4. Generally speaking, annual rainfall in the central part of the Sahel

Table 1. The distribution of significant positive and negative ΣNDVI-trends in valleys and plateaus/slopes in the north-western part of the study area.

	Study area	Valley	Plateaus and slopes
Total area (sq km)	508.9	115.8	393.1
Area with significant positive ΣNDVI trend (sq km)	69.9	54.1	15.8
Area with significant negative ΣNDVI trend (sq km)	160.1	5.1	155.0
Area with no significant NDVI trend (sq km)	439.0	61.7	377.3
% with significant positive NDVI trend		46.7	4.0
% with significant negative NDVI trend		4.4	39.4
% area with no significant NDVI trend		51.1	43.4

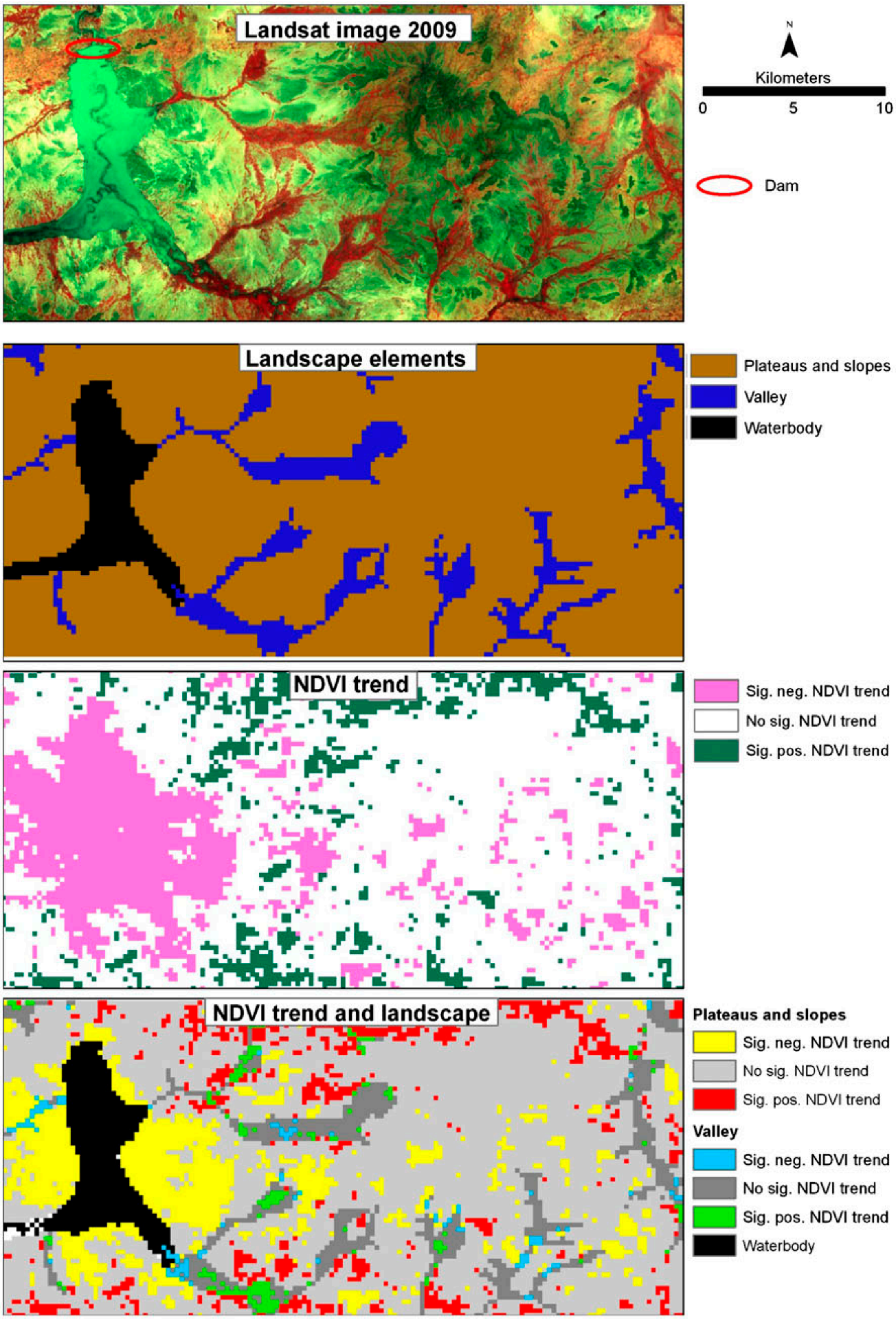

Figure 3. As Figure 2, but for the south-eastern part of the study area, close to the dam established in 2007 (shown). From top to bottom: a Landsat ETM image from September 2009, depicting the landscape elements in the study area, mapped on the basis of the Landsat ETM image, the distribution of significant positive and negative ΣNDVI trends, and the significant ΣNDVI trends overlaid on the two landscape elements.

Table 2. The distribution of significant positive and negative ΣNDVI-trends in valleys and plateaus/slopes in the south-eastern part of the study area.

	Study area	Valley	Plateaus and slopes	Waterbody
Total area (sq km)	678.1	85.3	553.4	39.4
Area with significant positive ΣNDVI trend (sq km)	71.3	12.9	58.4	0
Area with significant negative ΣNDVI trend (sq km)	150.4	6.9	105.2	37.6
Area with no significant trend (sq km)	606.9	72.4	495.0	1.8
% with significant positive ΣNDVI trend		15.1	10.5	0.0
% with significant negative ΣNDVI trend		8.1	19.0	95.4
% area with no significant trend		76.8	70.4	4.6

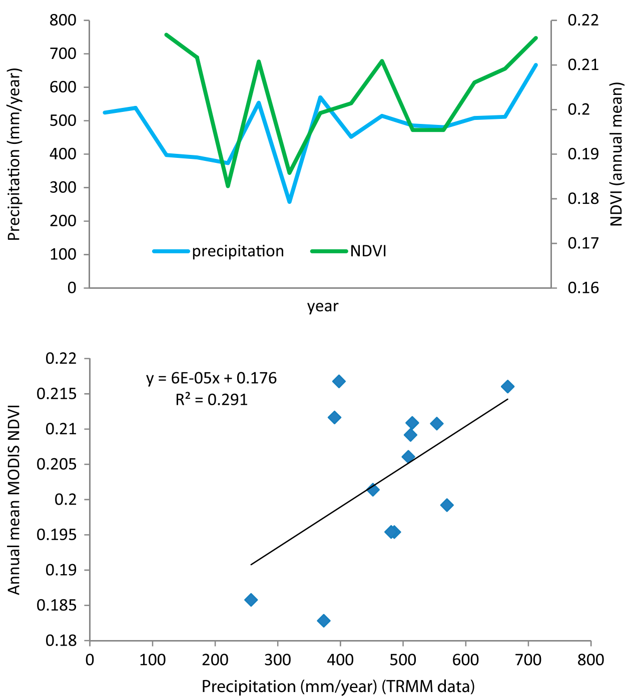

Figure 4. Annual rainfall in the study area for the period 1998–2012, derived from TRMM data, and ΣNDVI (for 2000–2012), aggregated to the TRMM resolution (upper). Relation between ΣNDVI and annual rainfall for the study area and for the period 2000–2012 (lower).

has been slightly increasing over the study period (Mertz et al., 2012).

While Figure 4 shows that ΣNDVI is positively correlated to annual rainfall, the degree of explanation is less than 30% [($p < 0.05$). ($r = 0.54$, $n = 13$, $p = 0.028$)]. For the short period considered the inter-annual variability is far greater than trends in ΣNDVI and annual rainfall, when averaged over the study area as a whole. As mentioned above, the distribution of rainfall over the season will impact on vegetation productivity, so rainfall variations may actually explain more than 30% of the variation in ΣNDVI.

5. Discussion and conclusion

The ΣNDVI-annual rainfall relation for the study area as a whole (Figure 4) shows that less than 30% of the variance in ΣNDVI is explained by annual rainfall, leaving ample space for explanations involving other factors, natural as well as anthropogenic. In the north-western part of the study area, the results show a very clear relation between landscape elements and ΣNDVI trends: more the 90% of the (MODIS-) pixels with significant negative trends are located on the plateaus and slopes, and more than 90% of the pixels with significant positive slopes are found in the valleys. This finding is consistent with the second explanatory model. The exact mechanism causing this outcome cannot be established on the basis of the available data.

In the south-eastern area, around Kekenene, this simple relationship between landscape elements and ΣNDVI trends does not exist. Significant positive and negative trends are found both in the valleys and on plateaus and slopes. This is consistent with the first explanatory model.

Thus, the reported findings may be said to confirm the idea that local human intervention, e.g. in the form of expansion of the cultivated area and increased grazing/browsing pressure, has had a greater impact on the observed ΣNDVI trends than changes in annual rainfall. While changes in annual rainfall have been shown to explain a considerable part of the variation of ΣNDVI at the regional and sub-continental scale (Fensholt & Rasmussen, 2011; Fensholt et al., 2013; Herrmann et al., 2005; Huber et al., 2011), human factors do play a significant role at this local scale as also suggested by others (Bégué et al., 2011; Seaquist et al., 2006). In the north-western parts, trends may be explained by processes closely related to landscape elements (such as increased run-off, soil erosion and vegetation redistribution), yet possibly triggered by increased grazing pressure, while in the south-eastern part trends appear to be mainly explained by land use/cover change.

The results from the north-western part of the study area, shown in Figure 2, strongly supports the second explanatory model, yet the exact mechanism cannot be established on the basis of the evidence presented here.

Further analysis will focus on whether the decrease in ΣNDVI observed on the plateaus and slopes is associated with loss of woody cover, and whether the increase in the valleys is associated with an increase in woody cover. To determine whether such a process may be caused by increased grazing pressure, more accurate and localized information on livestock numbers and migration patterns will be required. With respect to the south-eastern part, the observed change does not relate to landscape elements in any simple way. While this is consistent with the first explanatory model, it does not constitute a 'proof' of this hypothesis. Further work will focus on analysing the possible link between the land use history of the area and the trends in ΣNDVI. While such links may well exist, they are likely to be complex.

Overall the results confirm that while at the large spatial scale of the Sahel, and at a timescale of several decades, the ΣNDVI trends may to a considerable extent be explained by changes in annual rainfall, local human impact may be important at smaller scales.

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