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Implications of climate, land-use and land-cover changes for pastoralism in eastern Sudan

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ABSTRACT

This study examines the changes in climate and land-use/land-cover (LULC) along the livestock seasonal migration routes in El Gedaref region (eastern Sudan). Analysis of temperature, rainfall and aridity index (ratio of rainfall to reference evapotranspiration) data during 1941–2009 shows significant warming of the climate, increasing rainfall variability and seasonality, and intensifying aridity conditions during the start and end of the wet season. The somewhat recent enhancement of the overall (annual) rainfall has reflected only in the mid wet season and were caused by few very wet days, indicating increased rainfall concentration and possible risk of soil erosion. Such climatic alterations and variability have inherent implications for land-use and land-cover over the region. LULC changes were investigated using multi-temporal satellite imagery from three sites along the livestock routes. The major trends were drastic conversions of natural vegetation areas into large-scale mechanized agricultural land. This resulted in a progressive loss and degradation of grazing area in the entire region. Overall, the documented LULC changes may cause an irreversible loss of biodiversity and a depletion of other ecological services provided by natural vegetation. The results of this study provide useful information when seeking to resolve complex land-management issues.

1. Introduction

The combined impacts of climate and land-use/land-cover (LULC) changes have had devastating implications for pastoral people livelihood and ecosystems in East Africa (Galvin et al., 2001). For a region that has been hampered by poverty and lack of planning (Glover, 2005), such as El Gedaref, the potential effects of climate and land-use change are independently daunting. Therefore, the emerging challenge is not to consider each of these processes in isolation, but to evaluate the combined effects of these changes.

It is a long established fact that mobile pastoralism constitutes a rational use of the dry land environment. Pastoralists even profit from some of the harshest landscapes in the world. Compared to all other natural resource-based land uses in the drylands, pastoralism functions best within the prevalent context of climate change and variability. With the right policies, investment and support, pastoralism presents a logical adaptation in areas of increased climatic variability, and has an important role to play where other livelihoods are likely to fail (ODI, 2009).

LULC changes play a major role in climate change at global, regional and local scales. At global scale, LULC change is responsible for releasing greenhouse gases to the atmosphere, thereby driving global warming (Pew Center on Global Climate Change, 2008; Quaas, 2011). Therefore, analysis of local scale LULC change, conducted over a range of timescales helps to uncover general principles that provide an explanation and prediction of new LULC changes (Lambin et al., 2003). In this context, it is increasingly recognized that grasslands and rangelands deserve greater attention, not only for their large extent, widespread degradation and limited resilience to drought and desertification, but also for their potential capacity to sequester and store carbon in soils while supporting sustainable pastoral and agro-pastoral livelihoods for millions of people (FAO, 2009).

Climate change is a major driver for critical ecosystems particularly dry land areas where pastoral communities are found.

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Pastoralists are on the frontlines of climate change and are currently the most affected population in the Horn of Africa (SIM, 2010). Any adaptation agenda that does not respond to pastoralist needs falls short of addressing climate change adaptation for the region. In eastern Sudan, pastoralist communities are adversely affected by the social, economic, political and ecological crises in the country (Manger, 2001). These processes have led to rapid sedentarization, urbanization and the breakdown of their traditional livelihood system. Shazali and Ahmed (1999) stated that increasing numbers of pastoralists in El Gedaref region are losing their livestock, forcing many to leave livestock-rearing altogether. They also mentioned that the combination of increased climatic shocks, policies which hinder mobile pastoralism, and a lack of other viable livelihood options are pushing pastoralists out of the system. However, historically pastoralists constituted the wealthier groups in the country, and it was usually pastoralists who ruled over both the pastoral and sedentary populations (UNDP, 2006). Pastoralists' inherent adaptive capacity, which has enabled them to cope with climatic variability for centuries, is increasingly being compromised by policies which aim to sedentarize and modernize their livelihood system, ignoring the vital need for mobility and resource access (ODI, 2009; UNDP, 2006).

Pastoral communities remain among the most politically and economically marginalized groups in many societies (Nori et al., 2005; UNDP, 2006). The rapid and extensive expansion of rain-fed mechanized farming schemes in El Gedaref means that nomadic herders have lost a large share of their traditional grazing areas and migration routes (Sulieman and Buchroithner, 2009). Hence, the present study examines the changes in climate and LULC along the seasonal migration routes in El Gedaref region (eastern Sudan).

2. Study area, data and methods

El Gedaref State was taken to represent eastern Sudan (Fig. 1). This is an area where the presence of fertile clay soils has led to the development of highly profitable rain-fed grain cultivation, and whose rural localities are predominantly inhibited by people who base their living on various forms of pastoralism and agro-pastoralism (Sørbø, 1991). The natural vegetation of the area is classified as a woodland Savannah. This natural vegetation has largely been destroyed in the course of widespread clearance for mechanized crop cultivation, extensive burning and shifting cultivation (SKAP, 1992).

Agriculture is the main economic activity, followed by livestock raising in the traditional seasonal transhumant pattern, village livestock raising and, as a recent element, livestock raising by large-scale mechanized merchant-farmers investing surplus wealth in cattle (Sulieman, 2008). Significant groups of pastoralists follow a seasonal transhumance patterns in El Gedaref State. They herd camel, sheep, goats and cattle. During the rainy season, the herders and their animals migrate to the northern parts of the region looking for pasture in Butana area, which is a communal grazing land. On the average, they need to cross around 300 km. During the dry season, they travel to the southern part of El Gedaref region in search for pastures and water. The transhumance pastoralist groups use defined routes for travelling purposes and for resting and feeding of their livestock (Fig. 1). The problem today is that the animal routes are very narrow (100–150 m in width) and bare with very few rest places. Field visits showed that overgrazing and degradation are most noticeable along and in the immediate vicinity of the migration routes. Prior to the 1940s, the condition was totally different where the routes were

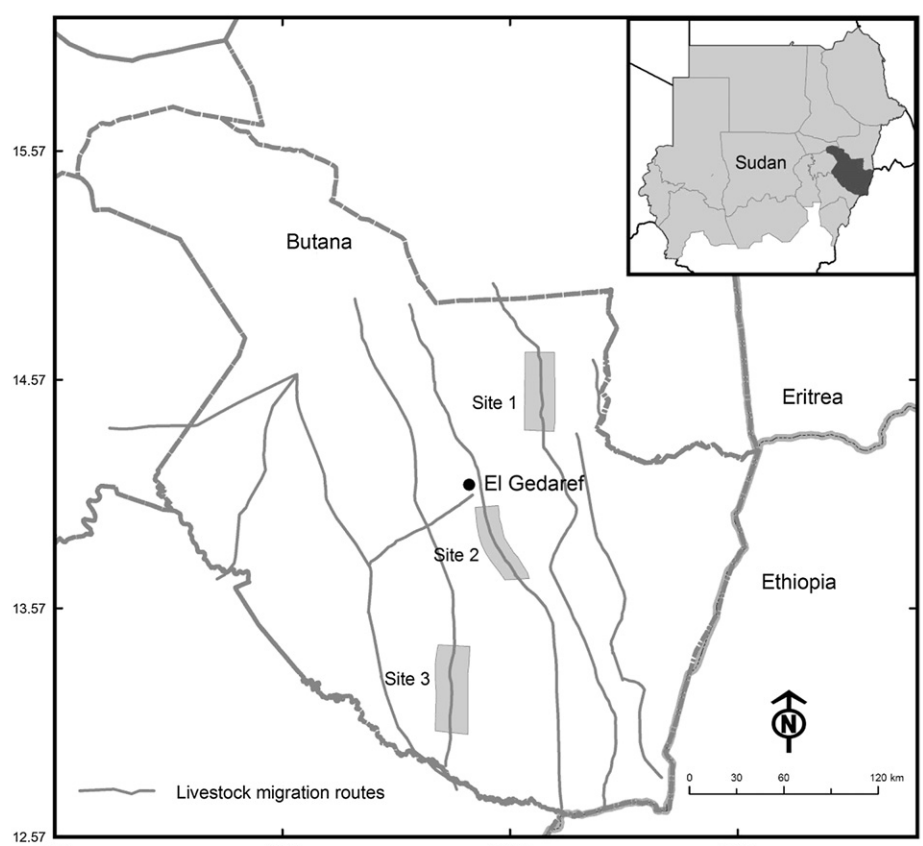

Fig. 1. El Gedaref map showing the seasonal livestock migration routes across the region and the location of three selected sites for testing LULC changes.

some kilometres in width and were covered with dense vegetation cover. However, the current situation is a result of encroachment of farmlands since the introduction of mechanized farming in the region in the mid 1940s.

Monthly rainfall and temperature data were obtained for the meteorological station of El Gedaref (latitude 14.03 °N; longitude 35.40 °E; altitude 600 m) from Sudan Meteorological Authority for the period 1941–2009. Standardized anomaly indices (SAIs) were calculated for the annual maximum (daytime), minimum (night-time) and mean temperatures as well as the rainfall data to assess the evolution of climatic departures from the normal (Jones and Hulme, 1996) for 1971–2000. The long-term trends and their significance level (α) were evaluated by the non-parametric test of Kendall tau (Kanji, 1997). A value of $\alpha \leq 0.05$ is set for this work to define the statistical significance. Whenever a significant trend existed, the linear regression was applied to find the trend rate. For the same data period, monthly and annual reference evapotranspiration rates were estimated using the temperature-based method given by Hargreaves and Samani (1985), which was found to approximate reliably the values of the physically-based method of FAO Penman-Monteith (Allen et al., 1998) in the arid and semi-arid parts of Sudan (Elagib, 2009). The aridity index designed by UNEP (1992) was calculated as the ratio of rainfall to reference evapotranspiration. The changes occurred in several indicators of climate change between two periods of equal lengths – old (1941–1978) and recent (1979–2008) – were examined. These indicators are median rainfall, rainfall variability as measured by the coefficient of variation, rainfall concentration or distribution over the year as assessed by expressing the monthly values as percentage of the total annual (Alvi and Elagib, 1996; Elagib, 2011; Elagib and Abdu, 1997) to give the percentage contribution, and the aridity state as classified by the UNEP aridity index. For the purpose of investigating the statistical significance between the medians (Median test), the IFA Services statistical tests (2010) were consulted.

To investigate the LULC change along the seasonal migration routes, three study sites were selected (Fig. 1). Their areas and distances from El Gedaref meteorological station are as follows: site 1 is 54,434 ha and 35 km, site 2 is 36,535 ha and 15 km and site 3 is 54,365 ha and 90 km. The selection of sites was largely based on the availability of the satellite imagery, as the study mainly depends on open-access archives, i.e. Global Land-Cover Facility: http://glcf.umiacs.umd.edu/. Cloud-free satellite imagery (Table 1) was used to detect the multi-temporal LULC change. All images were acquired at the beginning of the dry season, so that the phenological stages of vegetation cover are not too different between dates of acquisition. Moreover, the period that follows the crop harvests may be considered as the best time of the year for distinguishing the LULC types, notably because the contrast between agricultural land and natural vegetation is most practically distinct. However, there was one scene acquired during the late winter and beginning of the summer, i.e. 22 March, as shown in Table 1.

Table 1
Satellite imagery used for the multi-temporal change detection.

Satellite	Sensor	Path/row	Acquisition date	Spatial resolution (m)
Landsat 3	MSS	184/050	23-11-1979	60[a]
Landsat 3	MSS	184/051	23-11-1979	60[a]
Landsat 4	MSS	171/051	12-12-1989	60
Landsat 7	ETM	171/050	06-12-1999	30
Landsat 7	ETM	171/051	06-12-1999	30
Landsat 7	ETM	171/050	08-10-2006	30
Landsat 7	ETM	171/051	22-03-2003	30
ASTER	Terra	171/050	17-01-2009	15

[a] Resampled resolution.

Table 2
Description of major LULC types defined in the study area.

Class	Description
Bare land	Non vegetated areas formerly under cultivation and now abandoned due to degradation. This class also included unsuitable eroded areas characterized by bare rock and gravels.
Natural vegetation	Primary and secondary natural forest and woodland savannah appeared on some abandoned agricultural land, protected areas, areas along water courses and some depressions.
Agricultural land	Areas mainly under large-scale rain-fed mechanized farming covered with crop residue or late emerging grass species debris. These areas are cultivated with Sorghum and Sesame.

The imagery sets were geo-referenced to obtain optimal superimposition and minimize geographical deviation. Recent images for 2003, 2006 and 2009 were evaluated against ground surveys to obtain optimal superimposition and minimize geographical deviation. They were then used to geometrically rectify all the other images using an image-to-image adjustment process based on ground control points spread over each study site. Finally, the image-to-image errors were estimated to be at a sub-Landsat 7 ETM-pixel level (30 × 30 m). Identification of major LULC types prevailing in the study area since 1972 up to date (Table 2) was based on field surveys and interview with local inhabitants to obtain information on previous and current LULCs. In this respect, a group of 6–8 famers/villagers from each study site were interviewed. The survey was conducted during the first week of January 2010. Thereafter, the maximum likelihood method for supervised classification was applied to generate LULC. This method has proven to be a robust and consistent classifier for multi-date classifications (e.g. Shalaby and Tateishi, 2007; Wu et al., 2006). Post-classification technique was used to compare between the classified imagery. Post-classification is a term describing the comparative analysis of spectral classifications for different dates produced independently (Peterson et al., 2004; Singh, 1989). Despite criticisms focussing on accumulation of the inherent errors of each individual classification, this is the most appropriate method for comparing multi-source data, as each data layer can be generalized to a common LULC scheme before being compared (Petit and Lambin, 2001). Because neither historical aerial photographs nor ground data were available for the study sites, the accuracy of the LULC classifications was performed based on visual interpretation of unclassified images and later compared with classified images (Biro et al., 2011; Sulieman, 2010; Zheng et al., 1997) by means of commission and omission errors based on confusion matrices (Richards and Jia, 2005). Random samples of 100–110 points were obtained across each unclassified scene (site). In order to quantify changes of certain LULC type during certain time period, the calculation formula followed was:

$$\mathrm{LULCC} = \frac{\mathrm{LULC_b} - \mathrm{LULC_a}}{\mathrm{LULC_a} \times T} \times 100\%$$

where LULCC is the rate of change of a certain land-use/land-cover (LULC) type for a certain time period; the subscripts a and b denote the beginning and the end of a time period for LULC change investigation, respectively; and T is the time period. A positive value means that there is an increasing trend for a specific time period for an area of a certain LULC type; otherwise, a deceasing trend is occurring for the area assessed.

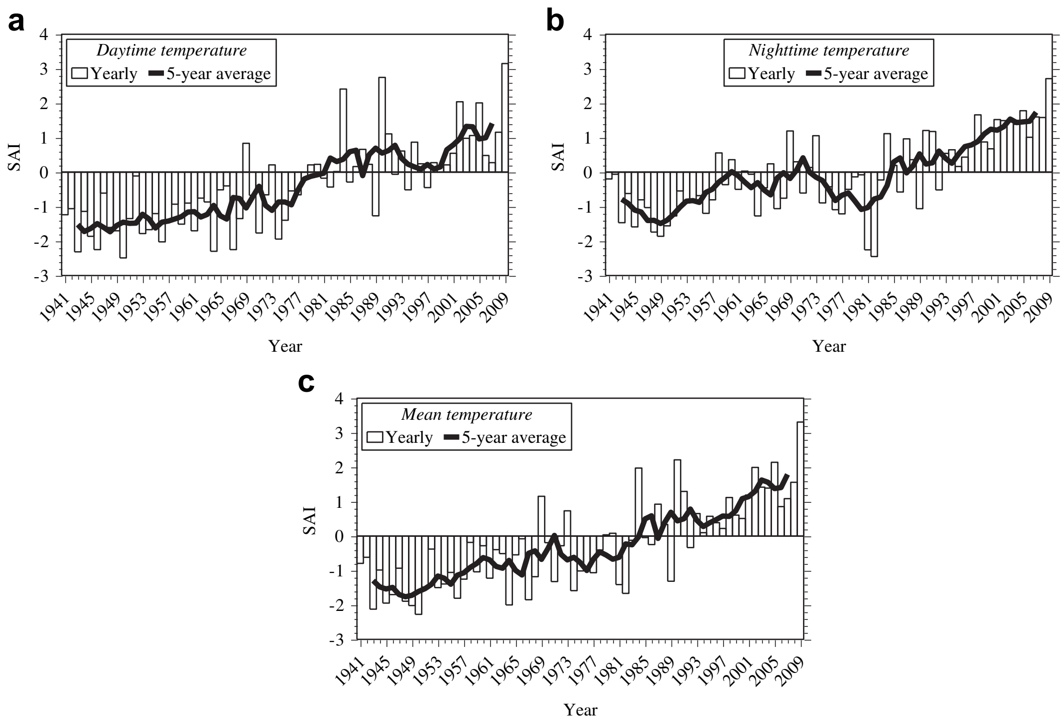

Fig. 2. Evolution of standardized anomaly indices of temperature.

3. Results

3.1. Climate change and variability

The time series of SAIs for both the temperature and rainfall are depicted in Figs. 2 and 3, respectively. Successive above-normal departures of nighttime and daytime temperatures are striking since around the mid-1980s, with the warming of climate more pronounced during the nighttime than the daytime. However, the rate of the increasing trend in the maximum temperature over the period of study is slightly stronger (0.25 °C decade^{-1}; $\alpha < 0.001$) than the corresponding rate for the minimum (0.21 °C decade^{-1}; $\alpha < 0.001$). Accordingly, the mean temperature series has a rate of 0.23 °C decade^{-1}, significant at $\alpha < 0.001$. Results by Elagib and Elhag (2011) show for El Gedaref: (1) that the rate of increasing maximum temperature anomalies is the highest in the country and (2) that the anomalies of the temperature variables are significantly, but negatively, related to the rainfall anomalies for the period 1971–2008, indicating concurrent warmth and dryness. During the last 30 years, the three time series show that 75% of the years were warmer than normal and the rate of increase is 0.53 °C decade^{-1} ($\alpha < 0.001$), 0.22 °C decade^{-1} ($\alpha = 0.045$) and 0.38 °C decade^{-1} ($\alpha < 0.001$) respectively for minimum, maximum and mean temperatures. These warming conditions have been observed to occur in all seasons (Elagib, 2010a). It is very clear that the year 2009 was the hottest year on record within 1941–2009. The shift in the temperature parameters from normal was 1.5–1.6 °C.

On the other hand, despite the noticeable above-normal years which count as 14 years during 1979–2008 (Fig. 3a), the time series of rainfall has an insignificant rate of increase for both the long-term period and the last three decades. The median rainfall augmented slightly from 1941–1978 to 1979–2008 by 18.8 mm in the annual value and 30.2 mm in the wettest month of August. Findings by Elagib (2010b) for El Gedaref showed that the annual rainfall is highly dependent on heavy rainfalls and is independent of light and medium rainfall events, indicating that heavy rainfalls are more likely to diminish in drought years and

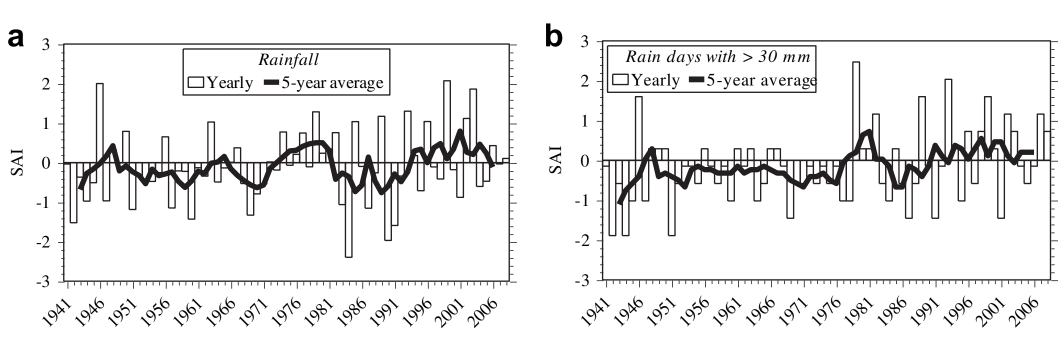

Fig. 3. Evolution of standardized anomaly indices of annual rainfall and rain days with more than 30 mm.

Table 3
Contribution of daily rainfall classes in % to the total annual rainfall for selected dry and wet years.

Year	0.1–1.0 mm	1.1–10.0 mm	10.1–20.0 mm	20.1–30.0 mm	>30 mm	Annual rainfall (mm)
1983	1.5	23.3	24.6	14.8	35.3	482.1
1984	3	25.5	16.3	23.7	32.5	319
1990	1.3	24.7	19.1	6.5	48.3	371.9
1991	2.4	25.5	22.6	31.6	17.9	418.8
1999	0.9	21.3	13.4	10.7	53.7	872.6
2003	0.3	14.7	16.7	30.7	37.5	846.7
2006	1.2	22.9	22.9	18.5	34.6	669.3
2009	0.8	21.1	8.8	8.3	60.9	532.7

increase in wet years, while light and medium events tend to vary independently of either drought or wet years. For instance, the Kendall tau test (two-tailed) indicates a significance level $\alpha = 0.032$ for the correlation between the time series of annual rainfall and rain days with >30 mm of rain (Fig. 3a and b). This can be authenticated by the results of Table 3 which show that increasing rain days with extreme rainfall (>30 mm) through time contribute mostly one-third to nearly two-third of the total annual amount.

These increases were accompanied, however, by reduced reliability and increased seasonality of rainfall. Rainfall has become more variable during the early (April and May), mid (July and August) and late (October) season as shown in Fig. 4. The coefficient of variation increased by 6.3 and 14.8% respectively for the annual and August rainfalls. In line with the annual rainfall departures from the normal over the last 30 years (Fig. 3), the distribution of rainfall over the season has also changed between 1941–1978 and 1979–2008 (Fig. 5). This figure shows how rainfall has become slightly more concentrated in the middle of the season, with the months of July and August contributing more to the total annual rainfall by 3.2 and 2.8%, respectively, against a decreased concentration in June and September by 1.9 and 3.2%, respectively. With respect to the recent period of 1978–2008, almost two-third of the annual rainfall is received in just two months (July and August) on the average (Fig. 5).

Tables 3 and 4 illustrate the observed variability and concentration by several examples of the combined results. The years 1999 and 2003 were the wettest and third-wettest years during the study period with annual rainfall of ~43% and ~39% above the 1980–2009 normal, respectively. However, the number of rain days between the two years for rainfall classes of 1.1–10.0 mm, 20.1–30.0 mm, and ≥0.1 mm were considerably different, i.e. 45 and 22 days, 4 and 10, and 80 and 57 days, respectively. Accordingly, the percentage contributions between the two years were 21.3% and 14.7% for the first class and 10.7% and 30.7% for the second class, while contributions of 53.7% and 37.5% are noted for the >30 mm class though the contributions made by daily rainfall events of >20.0 mm in the two years are different by only 3.8%. Although the driest years within the study period, i.e. 1984 and 1990, had almost equal contributions made by daily falls of >20 mm (56.2% and 54.8%, respectively), the breakdown of the contribution into the heaviest classes shows noticeably different results. Notwithstanding the year 2009 registered more rain in total compared to the dry years of 1983, 1984 and 1990, it had less rain days than 1983 and 1984 as well as appreciably higher concentration of rain in the extreme class (>30 mm). Of the 2009 rainfall, ~61% was recorded in 7 days only and merely 2 more days in the 20.1–30.0 mm class raised this percentage to ~69.

In view of the changes highlighted above, the vulnerability of the region to drought and the degree of aridity have also altered. This can be clearly discerned from the time series of the UNEP aridity index (Fig. 6). The average values of the index for the period 1979–2008 show that, among the wet season of April to October, four months (April–June and October) can be classified as hyper-arid, arid or semi-arid. Compared to the 1941–1978 conditions, a marked drop in the index occurred for June and September, with the aridity state for the latter month being more acute, thus shifting from the dry sub-humid class to the semi-arid class. Conversely, April and July conditions became more humid. It can be seen from Table 5 that the wet season in 2009 was as late and as dry as the drought years 1983, 1984 and 1990 until June. In this year, October was drier than average and was categorized as hyper-arid similar to the situation in the drought years of 1984 and 1990. Moreover, May was drier in terms of aridity index value, recording 0.042 compared to a value of 0.072 for 1984. Worth mentioning is that the area has experienced extended drought periods during the 2000s and that the drought is significantly linked to El Nino-Southern Oscillation (ENSO) (Elagib and Elhag, 2011).

The climatic changes and variability described above imply intrinsic changes in land-use and land-cover over the region, as will be exemplified in the following sub-section.

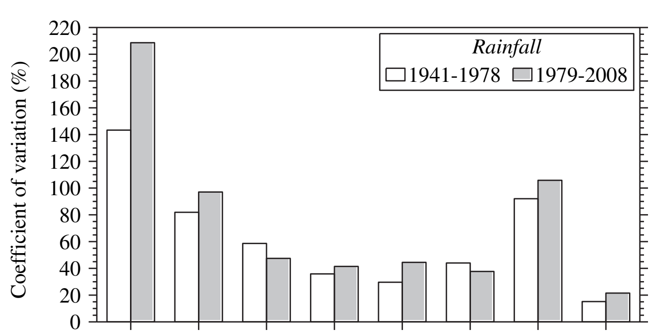

Fig. 4. Changes in inter-annual variability of rainfall between 1941–1978 and 1979–2008.

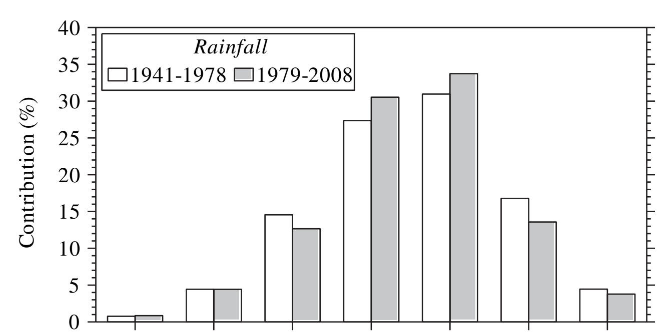

Fig. 5. Changes in mean percentage contribution of monthly rainfall to annual total between 1941–1978 and 1979–2008.

Table 4
Comparison between the number of rain days for different daily rainfall classes recorded for selected dry and wet years and the normal period of 1980–2009.

Year	0.1–1.0 mm	1.1–10.0 mm	10.1–20.0 mm	20.1–30.0 mm	>30.0 mm	Total rain days	Annual rainfall (mm)
1983	15	24	8	3	4	54	482.1
1984	17	22	4	3	3	49	319
1990	11	20	5	1	5	42	371.9
1991	17	27	7	6	2	59	418.8
1999	14	45	8	4	9	80	872.6
2003	8	22	10	10	7	57	846.7
2006	18	32	10	5	5	70	669.3
2009	11	23	4	2	7	47	532.7
1980–2009	12.7	27.8	8.4	4.5	5.6	59	610.7

3.2. Land-use and land-cover change

The cartographic and statistical analyses that show the general patterns of LULC change along the animal corridors are presented in Fig. 7. The maps depict changes in each of the main LULC classes during the study period. Main LULC classes are natural vegetation, agricultural land and bare soil. The natural vegetation cover represents the grazing resource during the passage of the livestock towards the communal grazing land in the north, i.e. Butana area. Fig. 8 presents the annual LULC changes for the duration of this period. In site 1, during the first study period (1979–1989), the percentage of agricultural land increased from 9.84% to 52.33% with about 43.18% increase per year. This is the most accelerated increment of agricultural land in all the study sites. During the second period (1989–1999) and third period (1999–2006), the dominant LULC class was bare land and agricultural land, while natural vegetation cover remains the least. It is clear that the increment of both agricultural land and bare land were coupled with a diminution of natural vegetation from 65.28% in 1979 to 9.69% only in 2006. Although the rainfall in 1999 was more than in 2006 in terms of total amount and rain days, the percent agricultural land for the former was less. A possible explanation could be that the distribution of rain over the season was better for 2006, with 34.6% of rain falling within the rain class of >30 mm compared to as much as 53.7% for 1999 (see Table 3), while the % bare land was equal though not necessarily covered the same locations.

In site 2 (Fig. 7), the area under cultivation dropped from 51.86% to 34.54% during the first period (1979–1989). However, it was the prevailing LULC class of the study thereafter 80.48% in 1999 and 77.35% in 2009, respectively. In contrast, natural vegetation, which in 1979 covered about 39.13% of the area, accounted for as low as 11.52% in 2009 only. Bare land is the minimal LULC class in this site. The annual rate of change for agricultural land in this site ranged from −3.34 to 13.30% while that for natural vegetation ranged from −0.34% to −6.67%. Again, site 3 (Fig. 7) shows progressive expansion of agricultural land during the last study period and gives an annual average growth rate of 6.72%. During the second period of the study, the natural vegetation cover shows a rapid increase from 6.47% in 1989 to 36.26% in 1999 which is the most rapid annual LULC change rate (46.04%) over the study period in the three sites. Natural vegetation cover had the chance to revive during the second period

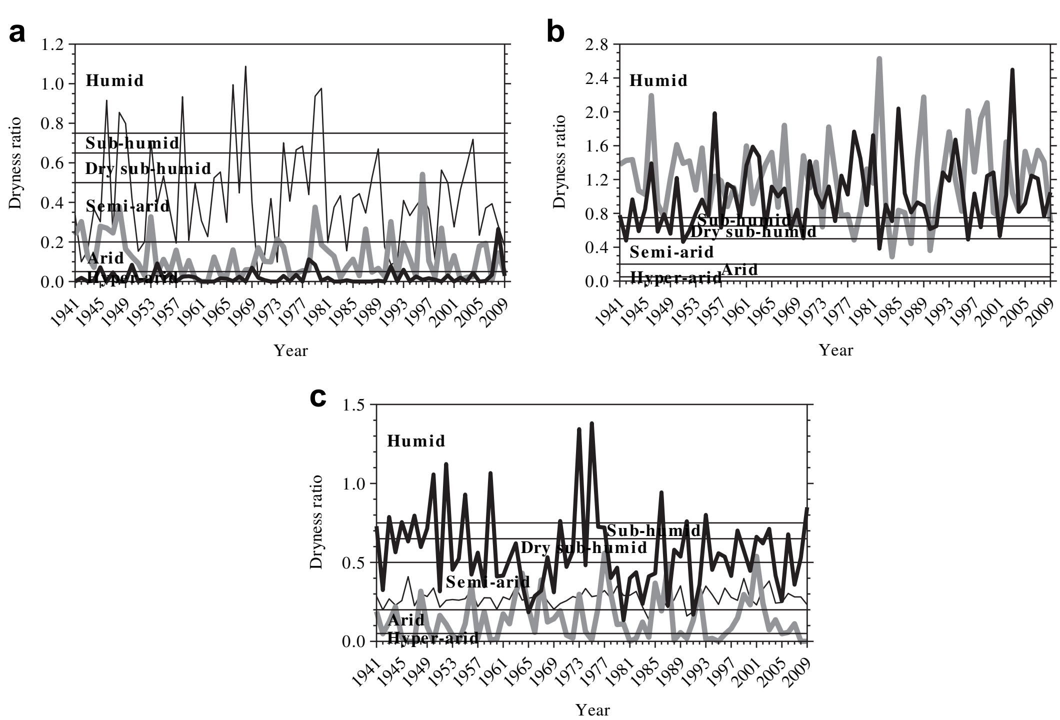

Fig. 6. Evolution of monthly and annual UNEP aridity indices for (a) Apr —, May ▬▬, and Jun —, (b) Jul — and Aug ▬▬, and (c) Sep —, Oct ▬▬, and year — (Dryness ratio: 0–0.05 Hyper-arid; 0.05–0.20 Arid; 0.20–0.50 Semi-arid; 0.50–0.65 Dry sub-humid; 0.65–0.75 Sub-humid; ≥0.75 Humid).

Table 5
Classification of the climatic conditions by UNEP aridity index for selected dry and wet years and the normal period of 1980–2009.

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Annual
1983	HA	HA	A	H	H	SA	A	SA
1984	HA	A	A	SH	SA	SA	HA	A
1990	HA	HA	A	DSH	SA	H	HA	A
1991	HA	SA	A	DSH	H	A	A	A
1999	HA	A	DSH	H	H	DSH	SA	SA
2003	HA	HA	DSH	H	H	SH	A	SA
2006	HA	A	SA	H	H	SH	A	SA
2009	HA	HA	A	H	SH	H	HA	SA
1980–2009	HA	A	SA	H	H	DSH	A	SA

HA = hyper-arid; A = arid; SA = semi-arid; DSH = dry sub-humid; SH = sub-humid; H = humid.

of the study. Recently, i.e. 2003, 35.19% of the site was left bare. Rainfall in 1999 was greater than that in 2003 by 25.9 mm and 23 rain days; however, the percentage of agricultural land for the former was less. Similar explanation to those for site 1 could also hold that the distribution of rain over the season was better for 2003, with days of >30 mm contributed only 37.5% of the total rainfall amount for the year compared to as much as 53.7% for 1999 (see Table 3).

Beside the overall accuracy, the omission and commission errors are shown in Table 6. Overall classification accuracies have been estimated to be in the range from 89.45% to 94.59%. The most accurately classified class has been found to be bare land. Omission errors obtained were ranged between zero and 16.22%, while commission errors varied between zero and 17.24%.

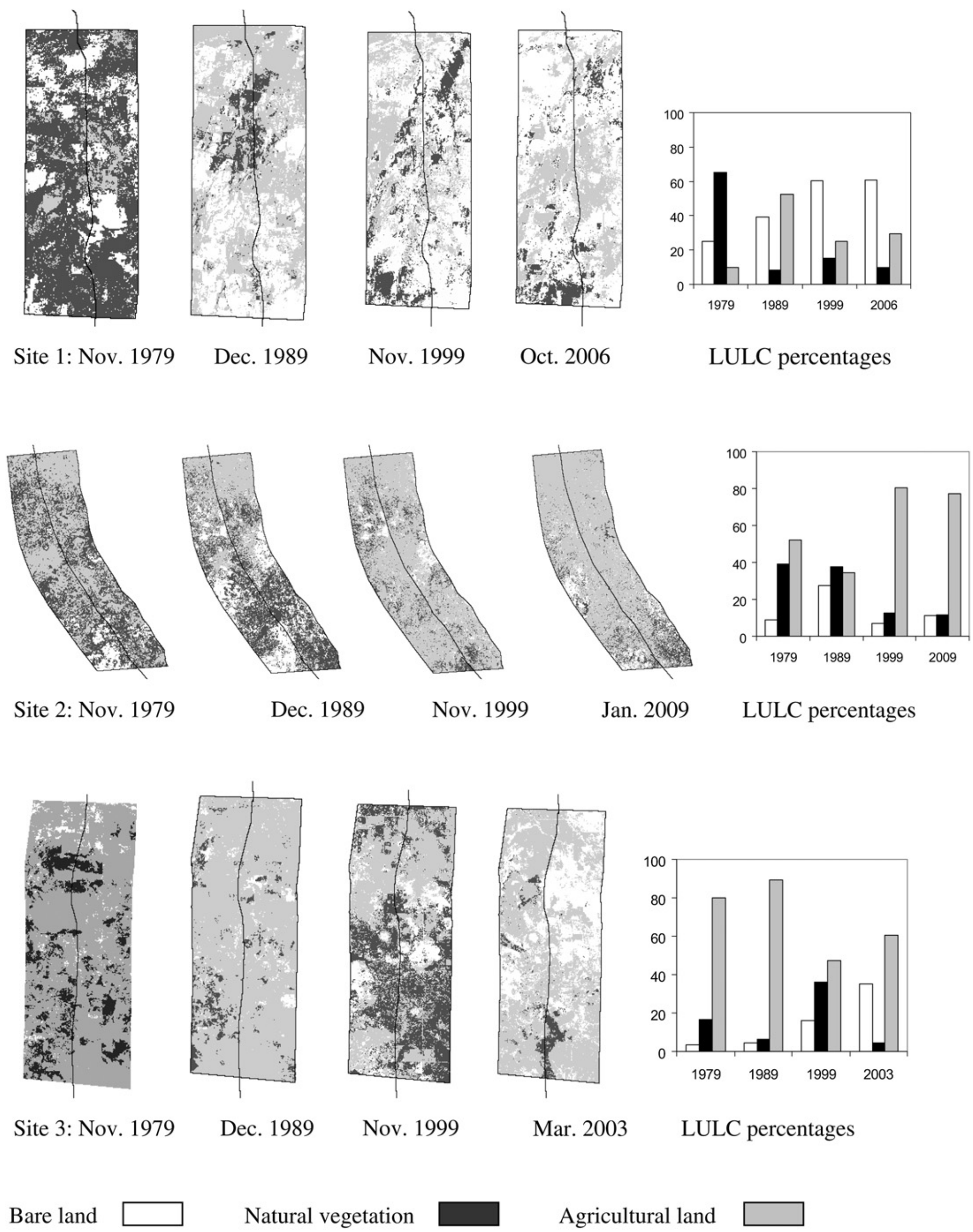

Fig. 7. Multi-temporal analyses of land-use/land-cover in three selected sites along the seasonal transhumance routes.

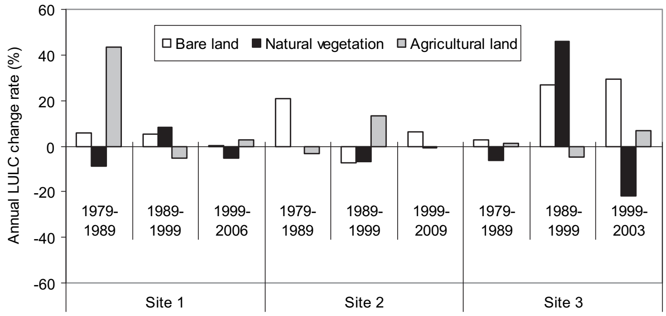

Fig. 8. Annual LULC change rates for the three study sites.

4. Discussion and conclusions

This study has presented convincing evidence of serious climate change and increasing variability in the eastern region of Sudan in terms of rainfall and temperature indices. Seemingly, the good fortune of this area, as expressed by Oliver (1965), in that rainfall is concentrated in the nighttime, i.e. when the weather is cool, has been outweighed by the prevalent warmth of air revealed by the minimum temperatures since about the mid-1980s (Fig. 2b). This is likely to enhance immediate soil moisture evaporation and downgrade the effectiveness of rainfall and recycling of antecedent moisture through evapotranspiration during the growing (wet) season (Savenije, 1995; Taylor, 2000). Moreover, the high intensity of rain resulting from few heavy showers, in addition to poor distribution of rain days over the season, may produce runoff in view of highly degraded soils by compaction resulting from increased human and animal pressures (Akhtar and Mensching, 1993; Akhtar et al., 1994). Thus, the soil would be deprived of infiltration, storage and deep percolation, consequently inhibiting the water supply to the plant.

The interpretation of multi-temporal satellite images was shown to provide a practical way for mapping and analyzing LULC changes in the three sites studied along the livestock migration routes. Computed percentages of LULC classes show a drastic expansion of agriculture, a rapid decrease in natural vegetation cover and a significant area left bare. These general trends of LULC change in the study area confirm the results of other studies in El Gedaref region (e.g. Glover, 2005; Larsson, 1995; Sulieman, 2010; Sulieman and Buchroithner, 2006). Analyses of possible drivers of agricultural expansion at the expense of grazing land in the region indicate that land-use policy is the main factor (SKAP, 1992). This bias in the settlement of disputes was institutionalized during the British colonial period when, in 1944, the Soil Conservation Committee recommended that: "where nomadic pastoralists were in direct competition for land with settled cultivators, it should be the policy that the rights of the cultivator be considered as paramount, because his crops yield a bigger return per unit area" (El-Tayeb, 1985). Although new rules and regulations were stated in El Gedaref; nevertheless, this approach is still followed.

This pattern of horizontal expansion instead of vertical expansion, i.e. increasing crop production per unit area, is one of the distinguishing features in many African countries (Leblanc et al., 2008; Ruelland et al., 2010). Suliman (1994) estimated that about 95% of forest in eastern Sudan were cleared to make way for massive agricultural schemes, with the trees eradicated as essential local sources of revenue from fuel wood and gum Arabic. Examples from Mali (Ruelland et al., 2010) and Niger (Leblanc et al., 2008) show that landscape units have been significantly cleared to extend the cultivated land and for firewood supply.

The category of bare land, used here, includes locations that were formerly agricultural now left bare such that they are not supporting natural regeneration of vegetation for many reasons, e.g. severe degradation, soil seed bank depletion. In sit 2, bare land is the smallest LULC class. This could be explained by the impact of human pressure because the site is located in the vicinity of El Gedaref town (Fig. 1; the capital of El Gedaref State), which is inhibited by 265,079 persons and surrounded by a dense belt of villages. Because there are no new fields to cultivate, people tend to cultivate unsuitable land, such as gravely-land, and also re-cultivate the degraded land. Basically, bare land is subjected to different land degradation processes. It is known that soil erosion potential is increased if the soil has no or very little vegetative cover and/or crop residues. Therefore, the significant proportion of land in sites 1 and 3 that were left bare are subjected to further degradation. In this respect, rehabilitation of the natural vegetation cover on bare land represents one of the most effective conservation measures.

In spite of the rapid increase in the area of land under cultivation and the increased proportion of land that left bare, there was some

Table 6
Accuracy assessment of LULC classes. Omis. = Omission error; Comm. = Commission error.

Site	LULC class	1979		1989		1999		2006	
		Omis.	Comm.	Omis.	Comm.	Omis.	Comm.	Omis.	Comm.
1	Bare land	7.32	4.88	9.68	6.45	16.22	13.51	5.56	2.78
	Natural vegetation	6.67	6.67	14.29	14.29	6.45	9.68	0.00	0.00
	Agricultural land	13.79	17.24	10.26	12.82	14.29	14.29	3.23	6.45
	Overall accuracy	83.13		79.78		80.42		94.27	
Site	LULCC class	1979		1989		1999		2009	
		Omis.	Comm.	Omis.	Comm.	Omis.	Comm.	Omis.	Comm.
2	Bare land	0.00	12.50	0.00	0.00	10.00	2.50	7.69	0.00
	Natural vegetation	6.25	9.38	2.94	5.88	5.56	8.33	0.00	5.71
	Agricultural land	12.82	0.00	5.41	2.70	5.71	11.43	2.94	5.88
	Overall accuracy	87.26		94.59		87.40		92.86	
Site	LULCC class	1979		1989		1999		2003	
		Omis.	Comm.	Omis.	Comm.	Omis.	Comm.	Omis.	Comm.
3	Bare land	5.26	2.63	5.71	11.43	2.94	0.00	5.41	2.70
	Natural vegetation	2.94	2.94	7.89	2.63	2.86	2.94	0.00	0.00
	Agricultural land	8.33	2.78	5.56	5.56	2.78	5.56	2.94	5.88
	Overall accuracy	89.45		87.24		93.61		94.59	

degree of recovery of the natural vegetation. Natural regeneration of abandoned agricultural land represents one of the major indicators of natural restoration process (Asefa et al., 2003; Chapman and Chapman, 1999; Rivera et al., 2000). However, even when there was an increase in natural vegetation (e.g. site 2, Dec. 1989 image), it was mainly owing to agricultural land abandonment. Such abandoned areas are not freely accessible to pastoralists because they are owned by farmers. In many cases (e.g. site 2), the natural vegetation clearance rate was very high, exceeding the average national clearance rate (FRA, 2005) for a country that has the highest deforestation rate in Africa (FAO, 2003).

The quantitative evaluation of climate and LULC changes in El Gedaref and their possible interactions have far reaching implications for pastoralism and ecosystems throughout eastern Sudan. El Gedaref region has become more prone to atmospheric drought and at the same time, the region is experiencing a drastic LULC change that leads to a significant reduction in grazing resources. Furthermore, it is clear that pastoralists are victims of marginalizing policies. Such a situation is pushing pastoralism out of the system. Nonetheless, the situation of a more dynamic climate and environment, in addition to the flexibility and mobility afforded by pastoralism, may increasingly provide security where other more sedentary models fail.

Overall, during the period of the study, natural vegetation had been significantly cleared to extend the cultivated land for crop supply. Nevertheless, LULC changes have differed markedly in terms of their patterns and trajectories in the three areas studied along the livestock routes. The general trend of agricultural expansion can be closely related to the state policy that favours the agricultural production at the expense of traditional livestock systems in the area. However, plant growth, development and yield in eastern Sudan rain-fed agriculture would highly depend on the state of the climate, particularly rainfall variables (Larsson, 1996). For example, according to El Gedaref State Ministry of Agriculture (2011), the 2009 sorghum yield was 220 kg/ha. This is only 42% of the normal yield although the annual rainfall amount was 87% of the normal. This emphasizes the importance of rainfall variables other than total annual or monthly, such as rain days, distribution over the season, etc, and the temperature levels (see Section 3.1 for discussion on climatic conditions in 2009).

However, instead of attempting to settle nomadic and semi-nomadic people in towns and villages, governments and policy-makers in Sudan might seek to rehabilitate pastoral livelihoods through a combination of traditional and novel approaches to land and livestock management (Brooks, 2006). Sustainable management of resources in El Gedaref that would allow successful coexistence between local users and conditions for environmental, social, and economic welfare is still a major challenge.

Although the current work has been conducted on a local scale and place specific with the intension to describe how rapid human modifications became a major driving force LULC with fundamental implications for current climatic conditions, it actually has its reflection on global change from different perspectives. Aggregated globally, multiple impacts of local land changes add up to be one of the most important facets of global environmental change and are shown to significantly affect the central aspects of Earth System functioning (Lambin et al., 2003).

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