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Development and application of a drought risk index for food crop yield in Eastern Sahel

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ABSTRACT

Drought is a common characteristic of the African Sahel whose agricultural productivity has been notoriously varying and declining as a result of this natural hazard. In this study, reasonably adequate climatic and food crop data for Sudan have been used to illustrate a straightforward method for assessing the recent past and within-season drought risk to sorghum and millet yields in Eastern Sahel. A drought risk index (DRI), which incorporates the drought occurrence frequency, duration, severity and areal extent in addition to the coping capacity and the production level, has been able to capture the large-scale droughts that induced crop failure and famines in the region during the recent history. Over 1970–2006, the drought risk was manifest in 15–21 years for sorghum and in 12–20 years for millet. In these particular years, the index is capable of explaining ∼52–69% and ∼32–66% of the variations in the regional states' yields of the two major food crops, respectively. There is a co-existence between the drought risk years and the warm events of El Niño – Southern Oscillation (ENSO). The results indicate clearly that drought conditions are capable of putting the crop yield at risk of suppression. On the state scale, the highest drought risk predominates in Northern Darfur on the average. Maximum DRI values of 47% for sorghum and 48% for millet occurred during the peak drought decade of the 1980s in the western part of the Eastern Sahel region. It is not hard to trace the low drought risk values for Gezira within the arid region to a large extent back to practised adaptation measure in the form of irrigation. On the regional scale, the maximum DRI was recorded in 1984 as 21% and 26% respectively for sorghum and millet. Generally, lower relation between millet yield and DRI, though significant, dominates in the western part of Sahelian Sudan, likely due to the inherent adaptation of the crop to such adverse growing conditions. In view of the regional agricultural expansion, even the average irrigation coping capacity of sorghum farming dropped from 8.0% in the early 1970s to around 6.0% in the first half of the 2000s. The model is also shown to enable short-term prediction by informing knowledge of pre-harvest quantities of crop yield from easily accessible data. The outcome of this study thus assists in providing a basis for drought mitigation and planning of benefit to authorities in agriculture.

1. Introduction

The African Sahel is characterized by natural climate variability and drought (Landsberg, 1975; Oguntoyinbo, 1981). In spite of the decades of research in the Sahel following the great droughts of the 1970s and 1980s (Landsberg, 1975; Tanaka et al., 1975; Nicholson, 1985; Hulme et al., 2001; Dai et al., 2004), there is still a disagreement about the prospects of the livelihood system in the region (Batterbury and Warren, 2001). The interplay between periods of meteorological drought and factors such as crop failure, food shortage, etc., which reveal the outcome of human activities, is the determinant of human hardship (Oguntoyinbo, 1981; Agnew, 1989). Being a region that relies on local agricultural production, it lacks food security when the weather occurs in abnormal episodes or becomes more variable (Thompson, 1975; Oguntoyinbo, 1981; Lansigan et al., 2000). Food insecurity is also anticipated under climate change (Brown and Funk, 2008). Droughts in this region

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are the main reasons for variations and decline in crop production (Davis, 1991; Larsson, 1996; Ayoub, 1999; Olsson et al., 2005; Balogun, 2011).

Research effort in crop modelling common to African farming systems is not well developed and is poorly represented (Challinor et al., 2007). One urgent issue for sustainable development, therefore, is to perform disaster-risk assessment (Birkmann, 2007) that can be used to differentiate between the estimated and perceived risk, i.e. to set forth estimates of probability, or to outline the possible outcomes of the disaster (Hultman et al., 2010). As regards agriculture, reducing the risk of crop losses from spatial and/or temporal drought is an important aspect of the Sahelian farming systems (Tabor, 1995). It is one of the pertinent research issues to be addressed in the African regions (Desanker and Justice, 2001). Nevertheless, it can be recognized from the literature survey that drought-risk analyses of crops pertinent to the Sahel still need to receive more attention. Identifying the drought risk of major food crops can provide a scientific basis for agricultural drought mitigation and planning (Wilhite, 2000; Zhang, 2004; Shahid and Behrawan, 2008; Lei et al., 2011).

Therefore, this study presents a method for assessing the recent drought risk to and short-term prediction of the two major crops grown in the Eastern Sahel (Sahelian Sudan extending between latitudes 10–16° N and longitudes 22–37° E). The area is populated by ~27.7 million people. Agricultural practices have expanded, and according to the Ministry of Agriculture and Forests (MAF, 2006), the area sown by the major food crop of Sudan (sorghum) can reach to ~7 million ha per annum in this region. Recent studies for the region show that the climate is already exhibiting significant changes evident by increasing temperatures (Elagib, 2010a), changes in rainfall amounts and patterns (Elagib, 2010b; Sulieman and Elagib, 2012) and prevalence of frequent and extended occurrence of droughts (Elagib, 2009; Elagib and Elhag, 2011). A regional study of meteorological drought and crop yield in this region has shown that just a mild drought (slightly below normal rainfall) could be responsible for sharp declines in the final sorghum and millet yields (Elagib, 2013).

2. Data and methods

2.1. Data

In this paper, the statistical data on sorghum and millet yields in addition to total planted and harvested areas were obtained from the Food and Agriculture Orgnization (FAO, 2011) for the period 1961–2009. Although the crop yield data from FAO are given on a country level, it could be assumed that they represent to a great deal the yield for Sahelian Sudan since this region is the overwhelmingly, agriculturally productive part of the country (Trilsbach and Hulme, 1984; MAF, 2006; CBS, 2008). However, further data for yield and sown, harvested and irrigated areas over 1970–2006 for the different states of Sahelian Sudan were available from the statistical year books of the Ministry of Agriculture and Forests (MAF, 2006) and Central Bureau of Statistics (CBS, 2008) of Sudan.

The monthly climatic data were collected from Sudan Meteorological Authority. Monthly mean maximum and minimum temperature and monthly rainfall were obtained for 1941–2010. Other data for Gezira (Wad Medani station) over 1970–2010 on sunshine and wind speed were also obtained. Warm and cold episodes for the ENSO, i.e. positive and negative sea-surface temperature anomalies, respectively, were obtained from JISAO (2013) to compare them with the developed DRI and evidence that it is capable of reflecting the droughts in the region. Data on Normalized Difference Vegetation Index over 1981–2009 were also downloaded from FEWS NET Africa Data Portal (FEWS, 2011), considering the maxima for the states under study.

2.2. The model

Drought performance is usually tested in terms of characteristic severity, duration, magnitude, intensity, frequency and area hit by drought using the theory of run of deviation from the mean (Chen et al., 2009; Edossa et al., 2010; Mishra and Singh, 2010). Accordingly, the magnitude is the sum of negative deviations in a duration of time, the intensity is the average magnitude of drought over the duration of drought, i.e. the magnitude divided by duration, and the severity is the magnitude of drought at a given time. The model of drought risk assessment used in this work is a re-configuration of the methods described by Zhang (2004) and Li et al. (2009). In the present study, the drought disaster risk to crop is considered as a multiplicative formula linking the potential adverse effects of drought as a product of six variables, namely (1) frequency, (2) duration, (3) severity, (4) spatial extent of drought (area coverage), (5) production level and (6) coping capacity. Thus, the drought disaster risk index (DRI) can be evaluated by the equation

$$\mathrm{DRI}\,(\%) = \mathrm{TF} \times A \times (1 - S) \times \mathrm{DS} \times (1 - \mathrm{CC}) \times \mathrm{PL} \times 100 \qquad (1)$$

where all the parameters are shown as ratios so that the DRI is a probability given in %, and that a higher value represents greater risk. The inputs of the model are defined as follows:

TF, time relative frequency of drought disaster which is the frequency of drought occurrence during the growing season over the study period;
A, crop drought area, which is the spatial extent of drought, i.e. the ratio of drought-affected cropped area to crop sown area;
S, severity of drought during the growing season is found as the ratio of total rainfall to total evapotranspiration for the whole season;
DS, relative length of dry spell during the growing season which is the ratio of the number of dry months to the length of growing season in months;
CC, capability of combating drought (e.g. adaptive (or coping) capacity by irrigation), simply defined as the proportion of the sown area equipped for irrigation;
PL, production level calculated as the ratio of yield residuals (detrended time series by linear trend) to the time trend yield. Only the negative values of PL indicate yield reductions due to drought, the absolute values of which were used in the DRI formula.

The studies by Zhang (2004) and Li et al. (2009) calculated an average value of the DRI. In the present study, the index is shown for individual yield-reduction years. In the calculation of DRI, Zhang (2004) did not include variables (4) and (6) while Li et al. (2009) considered only variables (1), (2), (5) and (6).

2.3. Drought index

The literature teems with innumerable drought indices, and none of these indices is free of limitations (e.g. Heim, 2002; Keyantash and Dracup, 2002; Kallis, 2000; Quiring, 2009; Mishra and Singh, 2010; Vasiliades et al., 2011). In the DRI model, Zhang (2004) used both daily rainfall and ratio of rainfall to water requirement during the crop growing season to define the drought variables. On the other hand, Li et al. (2009) employed the Palmer drought severity index (PDSI).

Drought is a relative condition of balance between rainfall and evapotranspiration in a particular area (Wilhite and Glantz, 1985; Wilhite, 2000). For this work, the aridity index (AI) of the United

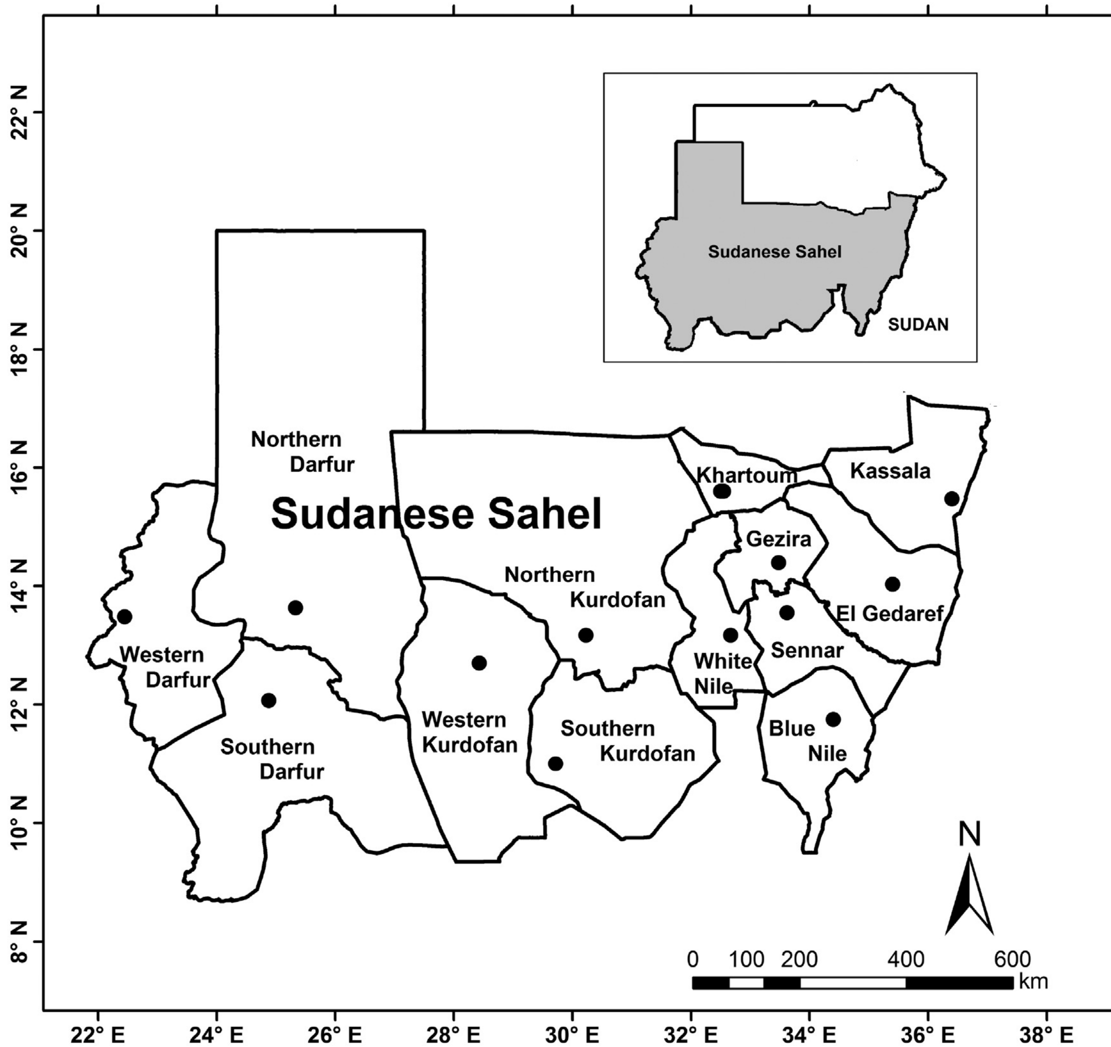

Fig. 1. Map of Sudan showing the location of the Sudanese Sahel (bound by 10–16° N), regional states and meteorological stations used in the calculation of UNEP aridity index.

Nations Environment Programme (UNEP) which is the ratio of rainfall to reference evapotranspiration (UNESCO, 1977; UNEP, 1992) was chosen to define the drought conditions. It delineates the bioclimatic limits. This index is derived from two important climatic elements for agriculture and reflects both the atmospheric supply (rainfall) and atmospheric demand (evapotranspiration), i.e. two important factors affecting the water budget of land surface (Zhuguo and Congbin, 2003). Unlike other drought indices, the use of UNEP AI serves the probabilistic nature of the present DRI model since the index is in the form of a ratio.

The reference evapotranspiration (ET_o) was calculated following the temperature method developed by Hargreaves and Samani (1985) and Hargreaves et al. (1985)–hereinafter referred to as HAR-85–which was successfully tested in the Sudanese conditions for the effect of site aridity (Temesgen et al., 1999). The method is also recommended as a proxy for the physically-sound method of FAO Penman–Monteith (Allen et al., 1998)– hereinafter called FAO-56. UNEP aridity index has been used for the assessment of drought in Sudan (Elagib and Mansell, 2000; Elagib, 2009a), the Sahel dry-lands (Hulme, 1996) and elsewhere in the world (Wolfe, 1997; Zhuguo and Congbin, 2003; Silva, 2004; Thomas, 2008; Sahin, 2012; Tabaria and Aghajanloo, 2013; Some'e et al., 2013; Mingjun et al., 2013; Nastos et al., 2013). For the sake of the regional analysis, area-weighted time series of the monthly UNEP AI were established for the growing season (June–October) based on the data for the 13 stations representing the different regional states of the Sudanese Sahel (Fig. 1).

2.4. Drought components and coping capacity

Fig. 2 of the monthly and seasonal aridity indices reflects the rainfall fluctuation and the consequent adverse effects that could be seen in the widespread crop failures. Similarly, the seasonal AI gives the value of S in the DRI equation. However, the representation of this term in the equation is $(1-S)$ since drought increases with decreasing S and the consequent impact on agricultural productivity is, hence, more probable. To determine the values that were plugged in the DRI equation for TF, A and DS, the three aridity criteria of the UNEP AI, namely hyper-arid, arid and semi-arid conditions (UNEP AI < 0.5), were adopted to define the condition of meteorological drought for the drought risk assessment. Fig. 3 exhibits the frequency of occurrences in the different drought categories. During the period of full data (1970–2006) for the drought risk assessment and the growing season of June–October, the regional data show that the hyper-arid class (AI < 0.05) contributed only 3.8% of the cases, the arid class ($0.05 \le$ AI < 0.2) contributed 27.6% and the semi-arid conditions ($0.2 \le$ AI < 0.5) recurred 34.1% times out of the total number of cases (total = 5 months × 37 years = 185 cases).

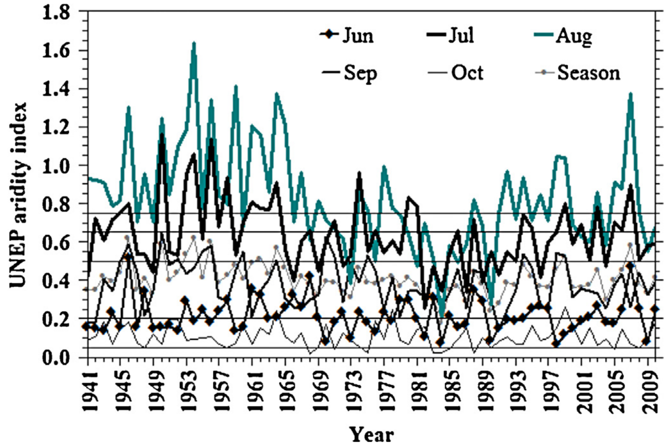

Fig. 2. Temporal variation in the regional UNEP aridity index for the growing season (June–October).

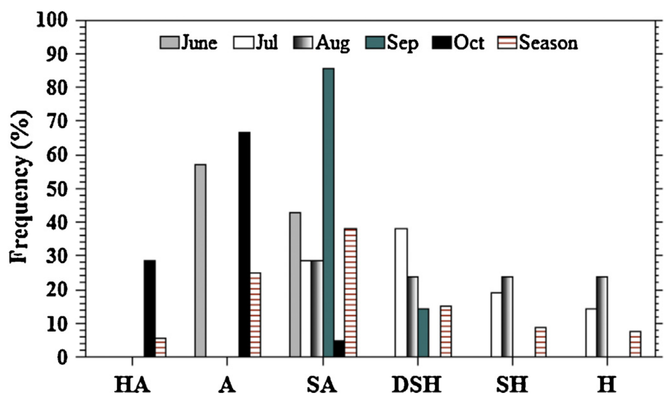

Fig. 3. Frequency of the aridity criteria during 1970–2006 (regional analysis). HA, hyper-arid; A, arid; SA, semi-arid; DSH, dry sub-humid; SH, sub-humid; H, humid.

Thus, the frequency of dry cases, which represents the value of TF, constituted two-third of the cases (65.5%). The DS values shown in Fig. 4 ranged from 0.4 (several years) to 1.0 (recorded in the peak drought year of 1984).

The calculation of the spatial extent of drought was based on the *S* values for the regional stations. Hence, the planted area was considered a drought area if the corresponding *S* was less than 0.5, i.e. again arid conditions as stated above. Fig. 5 displays the regional

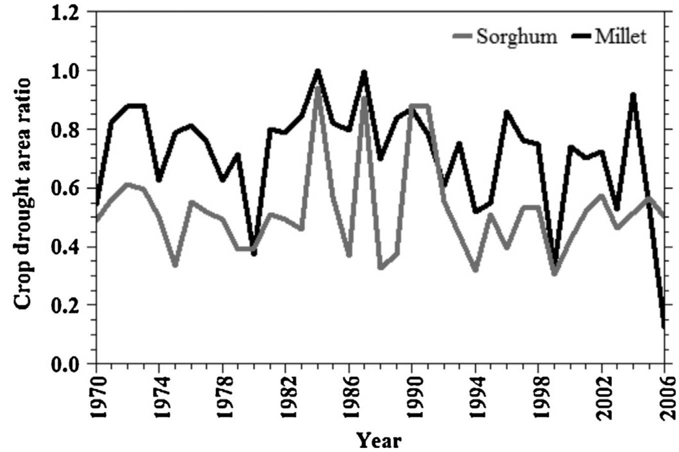

Fig. 5. Temporal variation in the regional crop drought area ratio (ratio of crop drought area to planted area).

crop drought area ratio. The time series of *A* values for sorghum is almost stable outside the period of extreme drought of 1984–1991 (average $A = 0.655$), thus the preceding period has average $A = 0.476$ whereas the following one has average $A = 0.493$. On the other hand, the *A* values for millet show a decreasing trend (Kendall tau = −0.234; $p = 0.041$). The available data from MAF (2006) and CBS (2008) show that irrigation is not practised for millet.

The time series of the coping capacity is shown in Fig. 6. If such a drought protection system, i.e. irrigation, does not exist or is not in operation, exposure and vulnerability are at maximum level (Tsakiris, 2007); then, CC is substituted as 0.

2.5. Production level

While the increasing trend in yield is assumed to be due to continuous innovation of agricultural technology (e.g. Nicholls, 1997; Lobell et al., 2011), a decreasing trend could be partly a result of climatic and partly owing to non-climatic factors. Examples of non-climatic causes include crop land mismanagement, weed, pest attack, plant disease, soil degradation, etc. (Agnew, 1989; Li et al., 2009). The removal of the effect of growing technology by simple linear de-trending is a widely-used technique by researchers (e.g. Zhang, 2004; Li et al., 2009; Sun et al., 2012). To remove the linear trend from the yield time series (Fig. 7a and b), the regional yield data were divided into two sets, that for 1961–1984 and that for 1985–2009 in the case of sorghum and 1970–1990 and

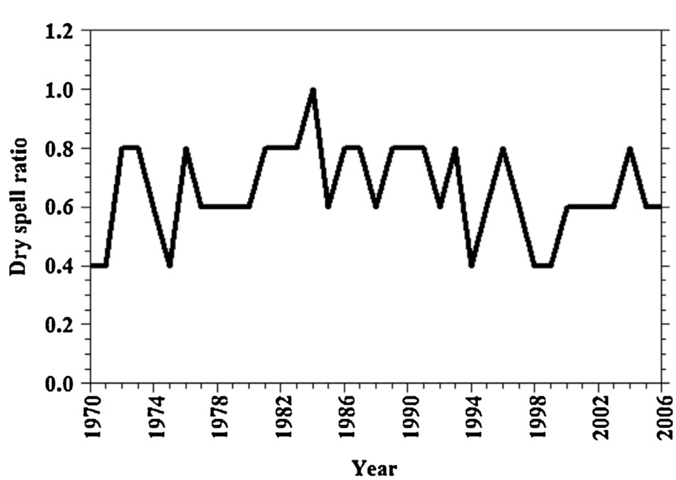

Fig. 4. Temporal variation in dry spell ratio for the growing season based on hyper-arid to semi-arid criteria (regional analysis).

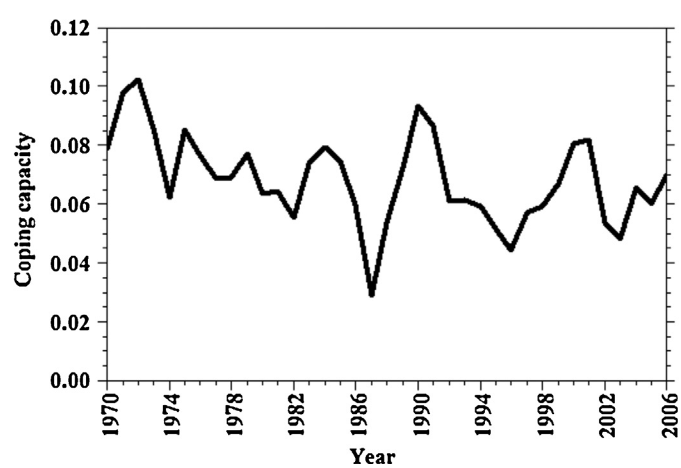

Fig. 6. Temporal variation in the regional sorghum coping capacity (proportion of planted area under irrigation).

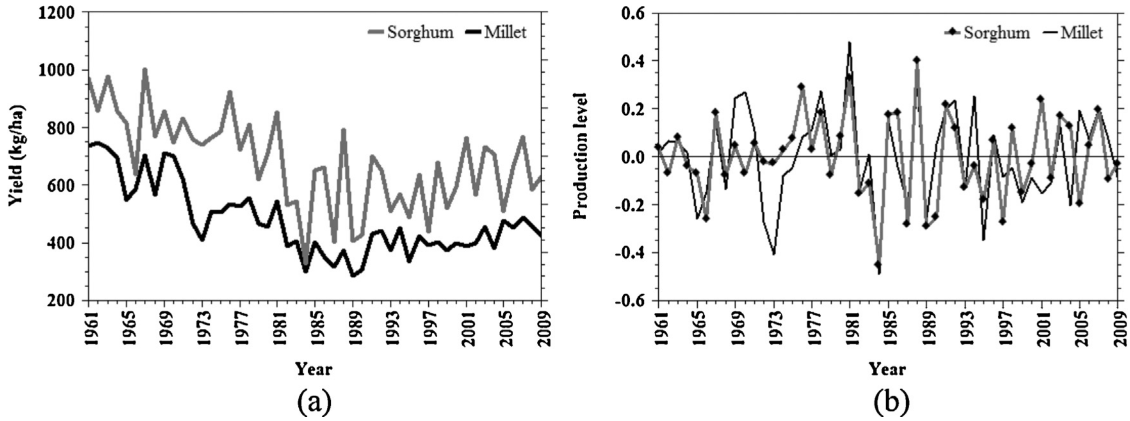

Fig. 7. Temporal variation in regional crop yield: (a) actual and (b) de-trended and normalized by the linear regressions for 1961–1984 and 1985–2009 (sorghum) and 1961–1990 and 1991–2009 (millet).

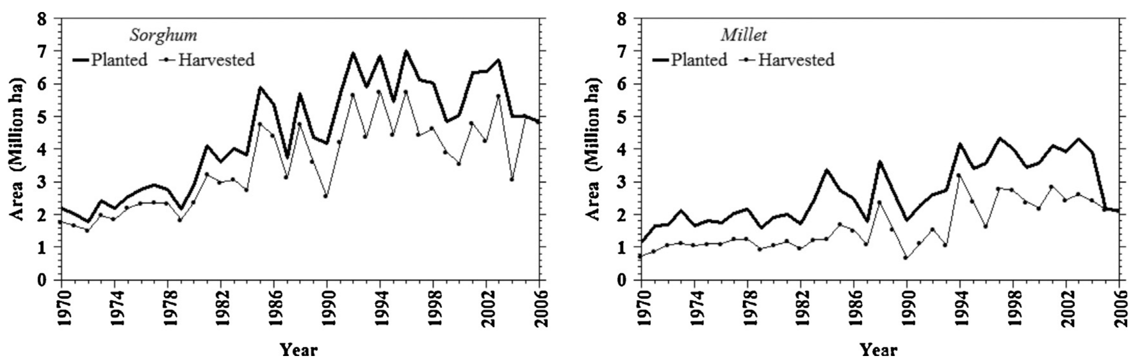

Fig. 8. Temporal variation in the regional planted and harvested areas.

1991–2009 for millet. The pattern showing a minimum value in 1984, with a decreasing trend before 1984 and an increasing trend afterwards, is remarkably similar to the rainfall variability in the Sahel (Munemoto and Tachibana, 2012) and drought conditions (Fig. 2). However, the yield data on the local scale (state) also indicate that the year of minimum yield may differ across the region as well as the crop under consideration, being 1984, 1987, 1990 or 1993.

Zhang (2004) defines PL as the ratio of actual crop yield of the district to the sum of yields for all other districts of the regions. For the sake of working with 'climatic yield', this definition was replaced herein by the normalized yield residuals as explained earlier. Both studies (Zhang, 2004; Li et al., 2009) considered the production level as (1 – PL) based on the view that a region with high production level of crop has high management level, high drought disaster combating capability and low potential loss of yield. However, the present study uses PL instead for several reasons related to the Sahel region. First, droughts have higher negative impact on the local economy of the higher food productive areas (Gray and Kevane, 1993) compared to a lower food productive area, especially if the coping capacity is low. Second, in addition to this economic variable, there is a strong linkage between drought and domestic food production (see Section 1) and famine in Sudan (Webb et al., 1991; Gray and Kevane, 1993). Third, the coping capacity decreases with increasing cropped/harvested area through time (Figs. 6 and 8). In fact, the CC values for 1970–2006 are always less than 10%, indicating the high dependence of the regional production on rain-fed agriculture. During the 1970s, the average CC was 0.080; then, the decadal average retained a value of 0.060–0.064. The records show decadal minima of 6.2, 2.9, 4.4 and 4.6% for the 1970s, 1980s, 1990s and 2000s, respectively.

3. Results

3.1. Drought risk to crop yield on the region-wide scale

Fig. 9 shows the regional time series of DRI for sorghum and millet by which it is possible to examine the evidence of drought impacts. A look at the years which record risks is instructive. These years match the years and periods of drought encountered in the country in particular (Elagib, 2009a; Elagib and Elhag, 2011) and in the Sahel region in general (Landsberg, 1975; Nicholson, 1985, 1993; Dai et al., 2004) in the recent history. They indeed reflect

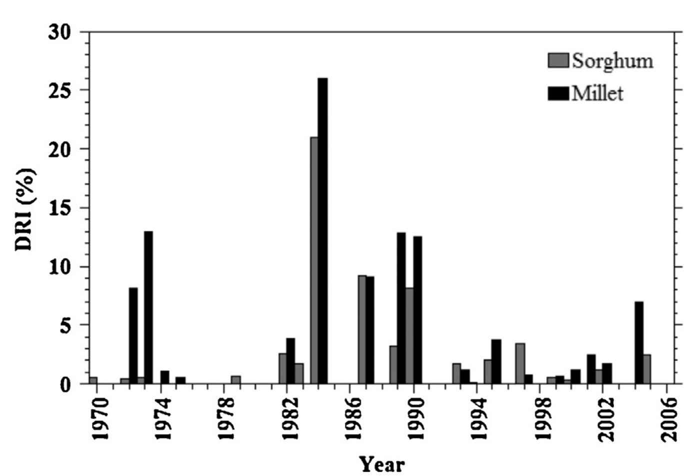

Fig. 9. Temporal variation in the regional drought risk index.

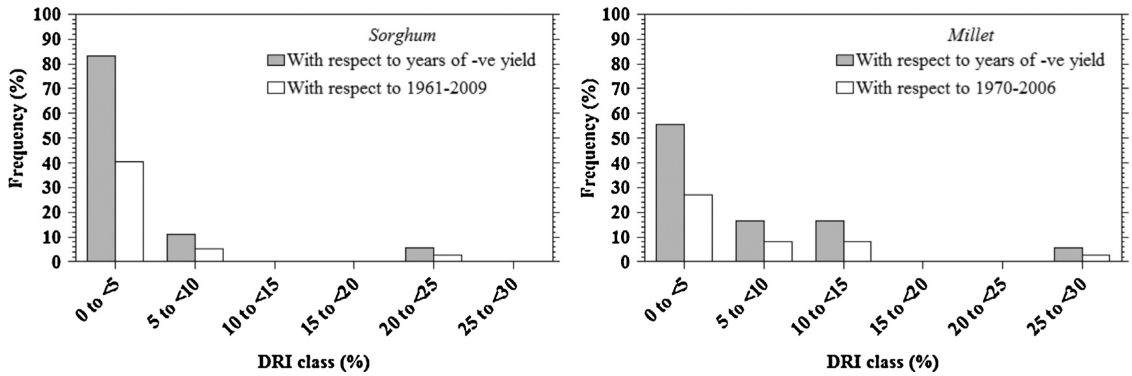

Fig. 10. Frequency distribution of the regional drought risk index.

the droughts which befell the region and provoked the most stark human tragedies and famines (Landsberg, 1975; Oguntoyinbo, 1981; Ibrahim, 1988; Webb et al., 1991; Gray and Kevane, 1993) in, for example, the early 1970s, the mid-1980s, the early 1990s and the early 2000s.

Particularly salient is that drought poses higher risk to millet that is grown under rain-fed conditions throughout the region compared to the partly irrigated sorghum. Hence, one fundamental explanation for this could be that the millet farming is not practised under irrigation. When this information is attached to Fig. 8, one can easily infer, at least in part, the reason behind the very small harvested area of millet in comparison to the planted area. Many parts of the region seem to be too arid to support millet cultivation under rain-fed conditions. For instance, similar to Western Sahel (Agnew, 1989), the sandy soils of western Sudan in which millet is grown may have high infiltration rates and low moisture storage, thus rainwater at the top surface layers of the soil dries up soon under hot conditions, especially during the early period of the rainy season.

It can also be noticed from Fig. 9 that both crops show climax of risk in a single year during the study period in the peak drought year of 1984, with DRI of 21.0% for sorghum and of 25.9% for millet. The decadal average DRI also reached the maximum in the 1980s, indicating a value of the order of 7.6% for sorghum and 9.1% for millet. During the study period, each decade experienced 3–6 and 4–6 drought episodes of negative impacts on sorghum and millet, respectively. For sorghum, successive 2–3 years with yield reductions can be observed in all the decades except the 2000s, while ‘millet drought’ in 3–4 consecutive years is noticeable in all decades except the 1980s. The longest drought duration for sorghum occurred during 1982–1984 and 1993–1995. Extended periods of ‘millet drought’ present in the time series had their maximum from 1972 to 1974, 1997 to 1999 and 2000 to 2002. Yield reductions due to drought occurred in 3 and 4 years during 2000–2006 for sorghum and millet, respectively.

The frequency distribution of the DRI values is shown in Fig. 10 in terms of percentage of risk years as well as of the entire data period. There were 18 drought episodes for each of the crops which caused negative impacts on the yield during the study period, i.e. nearly 49% of the years were characterized by yield reduction. Both distributions are inverted J-shaped. The millet DRI distribution evidences the higher degree of risk and the extremity of millet drought over that of sorghum. Eighty three percent of the sorghum risk cases were between 0 and 5%. Within the same range of DRI, millet yield experienced 61% of the drought episodes.

A regression analysis was carried out to clarify the relationship between the DRI and crop yield, as shown in Fig. 11 on a semi-log paper. The response of crop yield to drought conditions is such that yield declines with intensifying drought risk. While the line for sorghum is able to explain 63.7% (R^2) of the variations in yield, only 33.7% of variations in the millet yield are explainable by DRI though both linear relationships are statistically significant (Fig. 11). However, the fit of the relationship will be investigated on a state-to-state basis in the following section.

3.2. Drought risk to crop yield on the state scale

The method applied so far on the region-wide scale can also be employed on a smaller scale (e.g. the country states and provinces) for the sake of improving the spatial resolution and detailing the risks and impacts. This facilitates identifying the most drought-prone areas within the region (Fig. 12). Again the major droughts which were stated earlier are clearly reflected in the figures, peaking in the 1980s. The states worst impacted by drought in terms of yield reductions are Norther Darfur, Northern Kurdofan and Western Kurdofan along the border with the Sahara then come White

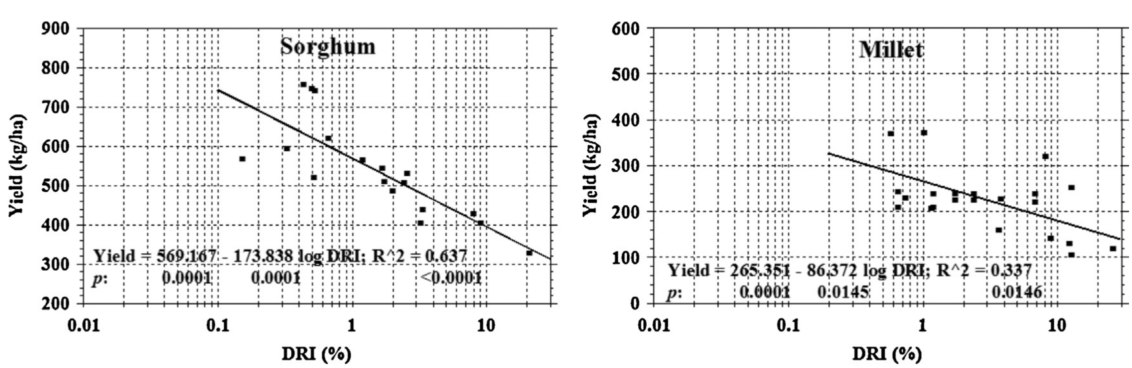

Fig. 11. Scatter plot of the regional crop yield versus the regional drought risk index. The line indicates the regression between the two variables. *p* represents the significance level of the regression coefficients.

Nile and Kassala. The average DRI for Northern Darfur is ~21% for sorghum and ~16% for millet. Highest 'sorghum drought' in a single year was recorded in Northern Darfur with a risk of 47% while the extremist 'millet drought' was registered for Northern Kurdofan with a risk of ~48%. On average, millet has higher drought risk index than sorghum in Kurdofan and White Nile. Noticeably low risk values for Gezira within the arid part of the region is attributable to heavy irrigation (coping capacity) where the maximum sorghum drought was indicated by a DRI of only ~10% in 1987. No risk is shown in 1984 for Gezira. The dramatic drought of the 1984's severity level resulted in low river-flow levels and increased irrigation demands beyond the carrying capacity of the canals, thus resulting in turn in the elimination of wheat from the rotation of the Gezira Irrigation Scheme (Hamad et al., 1986).

In general, yield reductions due to drought occurred during 1970–2006 in 15–21 years in the case of sorghum and in 12–20 years for millet (Tables 1 and 2). The tables also give the linear equations of the semi-log relationships between the yield and DRI for the regional states. These results authenticate the validity of the general fit of the relationship between the two variables at both region-wide and state levels. The justification for the log-linear fit is that DRI exhibits extreme skewness, i.e. J-shaped distribution, as shown in Fig. 10. It could be inferred from the relationships that drought accounted for more than 50%, with a maximum of ~69%, of the variations in the sorghum yield. On the other hand, 32–66% of the yield fluctuation values below the time tendency of millet yields can be explained by the drought risk. All the R^2 values of less than or equal to 45% are a character of the millet yield-DRI relationships for the western part of Sahelian Sudan (Kurdofan and Darfur). The weaker relation and lower significance can be explained by the fact that the crop appears to adapt to inadequate moisture that limits the production (Gregory, 1982; Blum and Sulivan, 1985; Baltensperger, 2002). Millet is grown under the most adverse conditions around the world in areas characterized by short growing season, high temperature, low and erratic rainfall, and sandy and less fertile soils (Gregory, 1982). These factors made millet production popular in the arid and semi-arid countries surrounding the Sahara Desert in western Africa and the Sahel as mentioned earlier in Section 3.1.

3.3. Testing the suitability of UNEP aridity index and DRI

Ghazanfari et al. (2013) found that the UNEP index classifies some areas drier than predicted by land surface models, which incorporate the role of vegetation and soil in the partitioning of precipitation into evaporation, runoff and infiltration. In their study, they used the method of Thornthwaite (1948) to quantify the evapotranspiration, which is likely over-estimated since it is not adjusted for site aridity, thus being partly a reason for the deviation noted for the UNEP AI. There might be a limitation to the use of reference grass evapotranspiration (ET_o) instead of crop evapotranspiration (ET_c); however, the dearth of the latter information should be recognized. In the present study, this limitation can only be tested for Gezira area in the central arid part of the region where sorghum crop coefficients are published by Ahmed et al. (2007) for use with reference evapotranspiration estimated with FAO Penman–Monteith method. This method is applied in the present study using solar radiation formulae specific for the station of Wad Medani in Gezira (Elagib et al., 1999; Elagib, 2009b). Hence, a comparison was made between the DRI values obtained by both ET_o and ET_c rates (Fig. 13 and Table 1). Although all evapotranspiration methods yield essentially significant linear relationships, the use of ET_c increases the R^2 of the yield-DRI regression line by 4% and 2% from those established using ET_o-FAO-56 and ET_o-HAR-85, respectively. Moreover, a comparison between the different DRIs indicates a mixture of higher and lower values of DRI using ET_c. ET_o-HAR-85 yields DRI values of the order of 0.758–1.251 (average = 0.983) of those corresponding to ET_c and values of 0.774–1.470 (average = 1.003) times those incorporating ET_o-FAO-56. This means that (1) the form of the yield-DRI relationship remains the same regardless of the evapotranspiration method used herein and (2) the results emanating

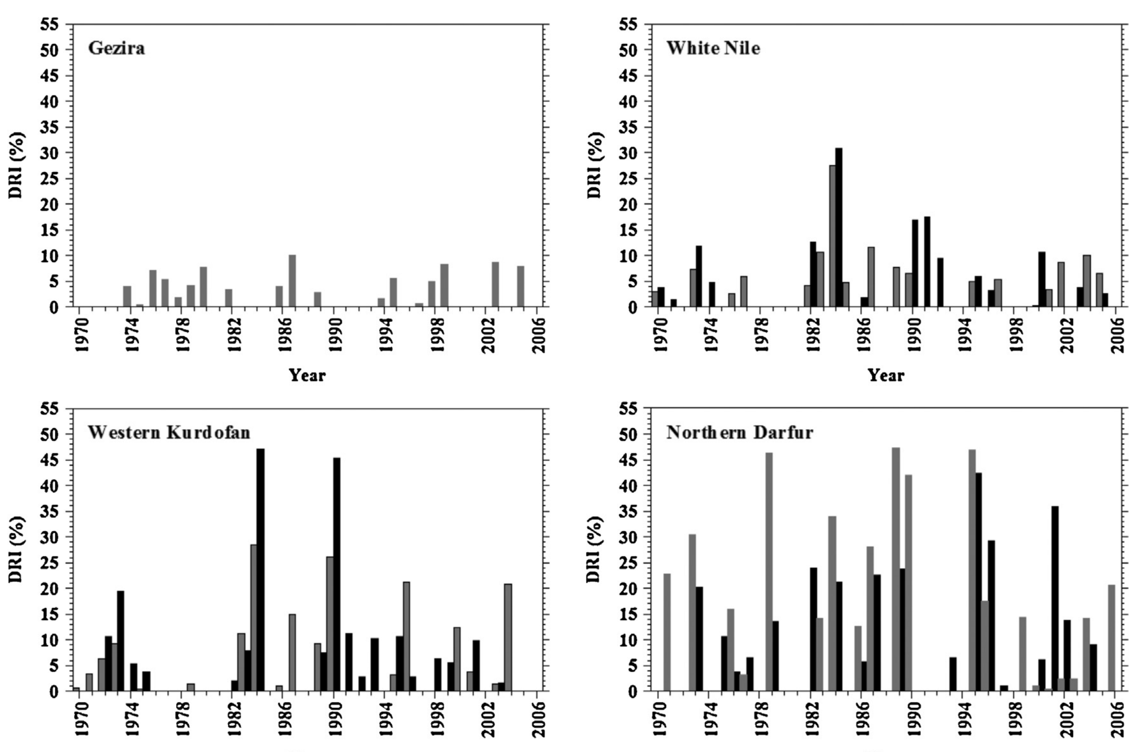

Fig. 12. Temporal variation in the drought risk index for sorghum (grey) and millet (black) for index states of Sahelian Sudan.

Table 1
Relationship between sorghum yield and drought risk index in the form of yield = $A + B \log \text{DRI}$ for the region and the states. The calculation of p of R^2 is based on two-tailed probability values.

	NOYRY[a]	A	p	B	p	R^2	p
Region	18	569.167	0.0001	−173.838	0.0001	0.637	0.0001
Kassala	17	755.418	0.0001	−176.523	0.0001	0.540	0.0008
El Gedaref	19	490.320	0.0001	−130.620	0.0001	0.520	0.0005
Gezira (ETc)	18	1045.501	0.0001	−295.626	0.0001	0.607	0.0002
Gezira (ETo-HAR-85)[b]	18	1042.143	0.0001	−296.686	0.0001	0.587	0.0002
Gezira (ETo-FAO-56)[c]	18	1040.156	0.0001	−288.774	0.0001	0.567	0.0003
Sennar	17	587.258	0.0001	−178.000	0.0001	0.599	0.0003
Blue Nile	21	473.770	0.0001	−164.777	0.0001	0.573	0.0001
White Nile	18	785.738	0.0001	−409.120	0.0001	0.578	0.0003
Northern Kurdofan	17	282.402	0.0001	−162.199	0.0001	0.685	0.0001
Southern Kurdofan	15	451.539	0.0001	−178.604	0.0020	0.522	0.0023
Western Kurdofan	18	521.866	0.0001	−250.985	0.0001	0.532	0.0006
Northern Darfur	20	342.240	0.0001	−119.032	0.0001	0.678	0.0001
Southern Darfur	20	527.678	0.0001	−228.450	0.0001	0.557	0.0002
Western Darfur	20	761.166	0.0001	−364.352	0.0001	0.615	0.0001

p: significance level of the regression and determination coefficients.
[a] NOYRY: number of yield reduction years used for calculating the DRI.
[b] HAR-85: using Hargreaves method (Hargreaves and Samani, 1985; Hargreaves et al., 1985).
[c] FAO-56: using FAO Penman–Monteith method (Allen et al., 1998).

from both physically-sound and simple ET_o methods, which are recommended in FAO-56, are comparable but may lead to both over- and under-estimation of DRI obtained using ET_c. However, the conclusion is tentative since it cannot be generalized to the whole region in view of lack of ET_c values for the rest of the states.

Sample figures of the annual cycles of both integrated NDVI (INDVI) and UNEP AI for the states where agriculture is practised under rain-fed conditions are shown below (Fig. 14). The INDVI was used earlier by Nicholson et al. (1990) to compare the vegetation response to rainfall in the Sahel. Here, the figure clearly shows that the patterns of the two indices during the wet growing season are very close. The relation between the seasonal INDVI and the drought severity (S) for all the states' data is significantly log-linear above AI threshold of 0.1 (Fig. 15). This would imply that the seasonal rain must reach at least 10% of the seasonal evapotranspiration in order to generate soil moisture that is usable by the vegetation to enhance the overall greening and production. Below this threshold the values are confined to Khartoum State in the northernmost part of the region (more arid) where both crops are not grown. Excluding the values for Khartoum, the equation is of the form

$$\text{INDVI} = 12.577 - 5.977 \log S \quad (2)$$

where the p-values of both regression coefficients are <0.0001 and the $R^2 = 0.459$ ($p < 0.0001$).

It is known that the Sahel rainfall and drought are significantly affected by ENSO and that the droughts occur following the large warm anomalies (Dai et al., 2004; Elagib, 2010b; Elagib and Elhag, 2011). Comparison of the years of both the drought risk in Fig. 9 and ENSO data from JISAO (2013) shows coincident risk following the

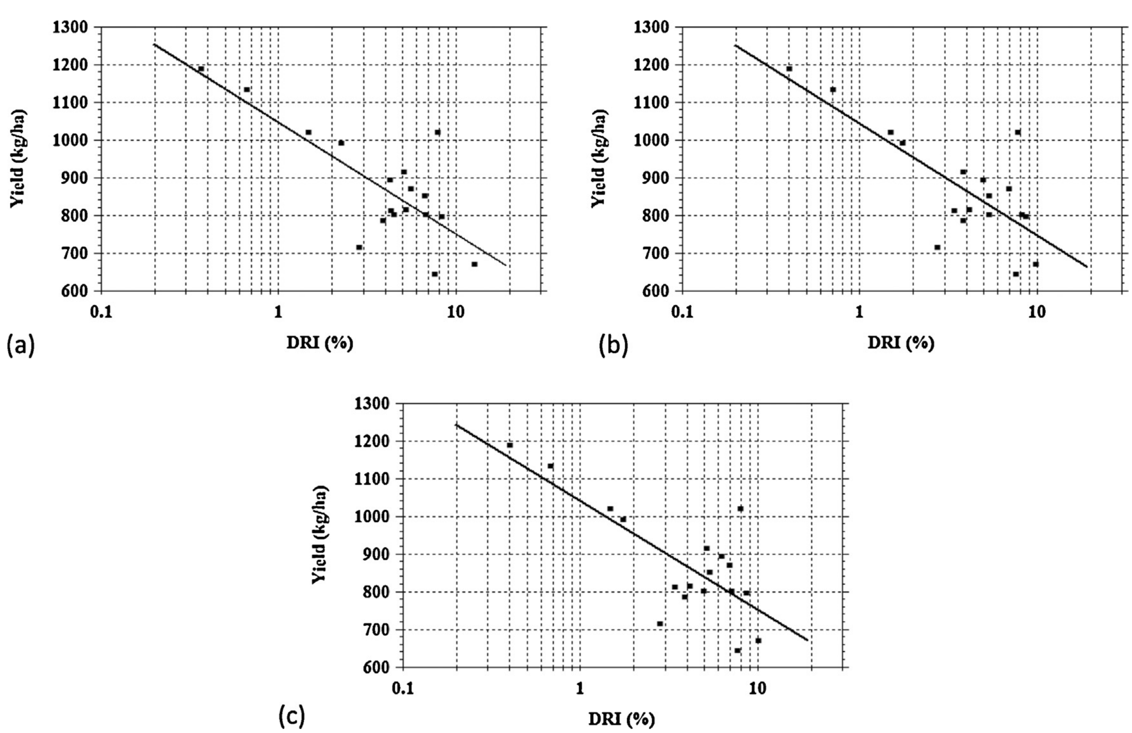

Fig. 13. Scatter plot of sorghum yield versus the drought risk index for Gezira using (a) ET_c, (b) ET_o by Hargreaves method and (c) ET_o by FAO-56 method. The line indicates the regression between the two variables.

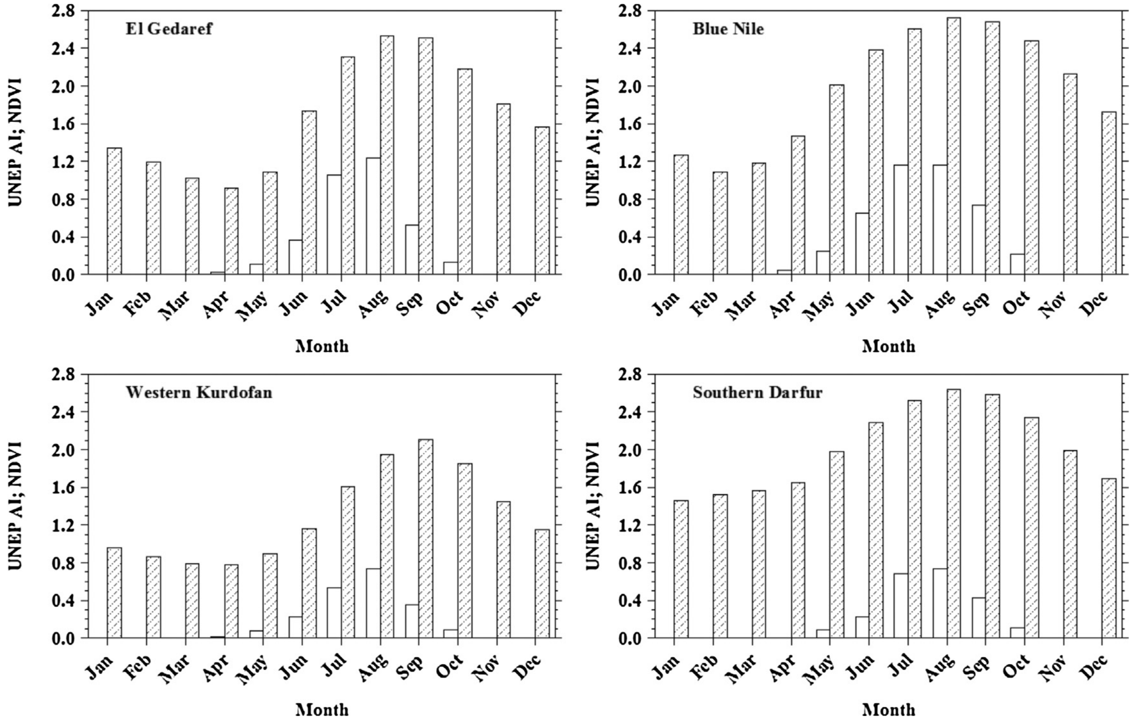

Fig. 14. Comparison of the average annual cycles of UNEP aridity index (solid bar) and integrated NDVI over the month (pattern bar) for index rain-fed states (1981–2009).

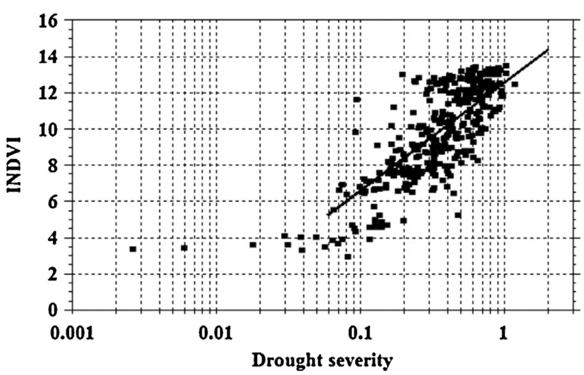

Fig. 15. Scatter plot of seasonal integrated NDVI (Jun-Oct) and drought severity (*S*) for all the states (1981–2009).

warm episodes of 1972–73, 1982–83, 1986–87, 1991–92, 1994–95, 1997–98, 2002–03 and 2004–05.

The above results indicate the suitability of the use of UNEP AI and the yielding DRI values.

3.4. Early warning of crop yield using DRI

Providing early warnings of agricultural drought plays an important role in drought preparedness planning and policy development (WMO, 2006). Prediction of drop in food crop yield at the beginning of the growing season helps initiating timely decisions regarding the import of food grains (Kumar, 1998). Unfortunately, analyses of model results of climate change for the African regions show no consensus and high uncertainty regarding the direction of precipitation change (Elshamy et al., 2009; Di Baldassarre et al., 2011) and other complications in the entire modelling chain (Di Baldassarre et al., 2011). Therefore, the resulting climate impacts “have not contributed greatly to the understanding of risk significance to decision-makers” (Conway and Schipper, 2011).

Table 2
Relationship between millet yield and drought risk index in the form of yield = *A* + *B* log DRI for the region and the states. The calculation of *p* of R^2 is based on two-tailed probability values.

	NOYRY[a]	*A*	*p*	*B*	*p*	R^2	*p*
Region	17	265.351	0.0001	−086.372	0.0145	0.337	0.0146
Kassala	–	–	–	–	–	–	–
El Gedaref	12[b]	359.606	0.0001	−123.734	0.0001	0.661	0.0013
Gezira	–	–	–	–	–	–	–
Sennar	18	374.011	0.0001	−152.395	0.0001	0.652	0.0001
Blue Nile	18	299.402	0.0001	−078.027	0.0001	0.527	0.0006
White Nile	15	480.159	0.0001	−212.781	0.0001	0.643	0.0003
Northern Kurdofan	20	123.889	0.0001	−054.675	0.0100	0.318	0.0096
Southern Kurdofan	15	333.560	0.0001	−105.345	0.0270	0.323	0.0271
Western Kurdofan	18	264.049	0.0001	−119.943	0.0130	0.326	0.0133
Northern Darfur	18	237.343	0.0001	−087.134	0.0140	0.320	0.0144
Southern Darfur	20	382.140	0.0001	−162.715	0.0010	0.446	0.0013
Western Darfur	17	773.758	0.0001	−299.047	0.0001	0.379	0.0085

p: significance level of the regression and determination coefficients.
[a] NOYRY: number of yield reduction years used for calculating the DRI.
[b] 1973–2006.

Table 3
Relationship between sorghum and millet yields and drought risk index in the form of yield = $A + B$ log DRI for the region. The calculation of p of R^2 is based on two-tailed probability values.

	NOYRY[a]	A	p	B	p	R^2	p
Sorghum							
June	18	640.260	0.0001	−217.048	0.0001	0.694	0.0001
July	07	620.856	0.0001	−247.672	0.0015	0.887	0.0015
June–July	18	623.588	0.0001	−174.232	0.0001	0.632	0.0001
Millet							
June	18	299.082	0.0001	−46.093	0.0500	0.220	0.0498
June–July	18	282.037	0.0001	−74.258	0.0350	0.249	0.0350

p: significance level of the regression and determination coefficients.
[a] NOYRY: number of yield reduction years used for calculating the DRI.

With the above views in mind, and in order for the present DRI to be of practical value for future possibilities, it has been tested for predicting the crop yield at an early stage of the growing season using the regional data. Table 3 shows that the drought risk model is capable of making drought early warnings of yield of both crops as early as June and July. Earlier findings indicate that drought in the early-to-mid growing calendar is harmful to crop, leading to yield reduction (Elagib, 2013). It is worthwhile mentioning that the yield reductions are captured in the same drought years that were indicated earlier. In the year of extreme drought (1984), the June, July and June–July drought conditions reveal emergence of risk to sorghum yield of 23.8, 16.8 and 40.9%, respectively. On the other hand, the likely risk to millet yield is respectively of the order of 29.6, 20.9 and 50.8%. Compared with the season-long assessment of risk (Section 3.1), the above results suggest that both the land-preparation and the initial crop growth stages are vital for the determination of the yield quantities.

4. Discussion

Downing et al. (1997) suggest that the constraint of the short-attention cycle, which they define as the attitude of drought planning that peaks a year after the drought and is then forgotten until the next crisis, may be overcome if drought becomes more frequent. Contrarily, the reality of the foregoing results for Sahelian Sudan contends this notion. While the drought events and associated crop losses in the region have been recurring in the region, the lack of contingency planning and the dependency on crisis management instead of risk management seem to have persisted similar to many sub-Saharan African countries (Wilhite, 2000). The reported drought risk in addition to distinctive geographic endowments (Collier, 2007), peculiar socioeconomic settings, political conditions and agricultural policies in sub-Saharan Africa (Hyden, 2007) and degraded soils (Ingram et al., 2008; Pretty et al., 2011) add to the product of food insecurity (Brown and Funk, 2008). Scenarios of global warming are likely to increase droughts in arid areas (Kallis, 2000). Recent predictions of future rainfall and temperature for Sudan under global warming show that rainfall in the growing season would decrease during June–August and increase in September–November, with continuous increasing trends in temperatures, thus negatively influencing livelihoods improvement and poverty reduction in the country (Chen et al., 2013). These scenarios are expected to result in a substantial crop yield loss (Hope, 2009) as a result of the deficiency of subsoil moisture during the critical crop growth stage (Glantz and Katz, 1977; Sivakumar, 1992). Since agriculture in the region is fundamentally rain-fed, these scenarios are likely to interrupt the start of sowing dates of crops, especially in view of the early warning results obtained in the present study. Gray and Kevane (1993) reported that most farmers in western Sudan lost their seed stocks during the 1990's drought as a result of failure of several initial plantings.

Since the recurrence of drought is inescapably a characteristic of the region, future plans should emphasize incorporating this factor in the agenda (Landsberg, 1975). In theory, Abdel Ati (1988) argues that there is no need for food production in Sudan to depend entirely on the rain-fed sector. To mitigate the negative effects of rainfall variability, and in turn, of economic recessions, Hendrix and Glaser (2007) suggest that the dependence of the whole of African agriculture on rainfall be reduced. Li et al. (2009) state three reasons for the high drought risk to crop yield in the African countries, namely "their arid climate, insufficient agricultural infrastructure and relatively poor management levels". Irrigation is crucial for mitigating drought (Bin et al., 2011). Areas having well-developed irrigation infrastructure have relatively low drought vulnerability (Lei et al., 2011). However, the data for Sahelian Sudan show that irrigation percentage has not improved along with the expansion of sorghum agricultural practices (Figs. 6 and 8). For Niger in Western Sahel, Sivakumar (1992) suggested that the water stress encountered by millet be terminated at or before flowering in order to ensure small yield reductions since the timing of rainfall is crucial for millet growth and yield. Gregory (1982) suggested that "increasing the size of the root system to exploit deeper water reserves [and] managing the existing water reserves more efficiently" can increase the millet grain yields. Nevertheless, the current adaptive capacity to drought in both the rain-fed and irrigated crop production systems could be improved by simple and effective solutions to prevent similar drought disasters in the future through, for example, rainwater harvesting rather than large-scale irrigation (Tabor, 1995; Mortimore, 2010). In the events of intermittent drought, which is more serious to crop than perennial drought since the former involves failure of rain at the time of watering the crops (El-Tom, 1986), such rainwater harvesting techniques may complement the deficit. For crops with high water demand, Elramlawi et al. (2009) showed that the use of water harvesting could be successful. Indigenous water-harvesting systems were also found sustainable as they raise yields through their nutrient harvesting effects, thus offering greater production security (Tabor, 1995; Niemeijer, 1998). However, the cost-effective of these technologies in agriculture should be evaluated in advance in terms of feasibility especially when the cultivation lands are far from the rainwater collection (harvesting) points.

5. Conclusions

This study has focused on how the concept of drought risk to crop can be captured into a quantitative measure through a straightforward model that incorporates a product of drought characteristics, namely the frequency, the duration, the severity, the spatial extent and the coping capacity, and the production level. Drought exhibits varying strength and significance across the Eastern Sahel since 1970, and the drought risk is seen to be particularly higher in the western states of the region. However, the relationship between yield and DRI is stronger for sorghum than for millet.

Considering the overall regional assessment, the DRI explains ~64% of the yield variations below the tendency line for sorghum compared to only ~34% of those for millet. The reason is that growing millet is favoured under harsh environments similar to those prevalent in the western Sudanese Sahel since the crop is adaptable to poor, droughty, and less fertile soils as well as to less coping capacity through irrigation. This can be realized from the R^2 for the millet yield-DRI relationships between the western and eastern states of the region which takes the ranges ~32–45% and 53–66%, respectively.

Wilhite (2000) highlighted the inadequate understanding of drought impacts as one of the major factors leading to reactive rather than proactive responses to droughts in sub-Saharan Africa. Based on the present data for the Sudanese Sahel during the recent past, the results obtained have marked implications for improving the drought security in the agriculture sector since they indicate corresponding drought risk in the region on a year-by-year basis. In the context of climate, the indicator presented herein can be used by the concerned authorities in their protection plans as regards the yield of two staple crops grown in Eastern Sahel. The risk model seems very promising in three aspects. First, it can provide a tool to diagnose the impacts on food production associated with drought, i.e. can be used as an index for early warning of crop yield by predicting the yield at an early stage of the crop growth. Second, it helps to bridge some of the gaps between the theoretical concepts of climate risk and decision making (Birkmann, 2007; Hultman et al., 2010). Third, it provides knowledge from easily accessible data.

Several recommendations arise from this study. It will be important to evaluate the risk on time scales of drought less than the month (e.g. dakads, weeks or days), as these time resolutions are more appropriate for measuring the dry spells within the different stages of the growing season. Drought risk to other crops (e.g. cash crops) can also be assessed. Due to inadequate data, this study has used grass reference evapotranspiration for examining the drought characteristics. Certainly, further improvement is likely by using crop evapotranspiration if data become available. However, based on the results obtained using crop evapotranspiration for a single state in the region, the DRI values are on average reasonably approximated by those resulting from grass reference methods of evapotranspiration. The range of the aridity index used to define the drought inputs in the model was confined to AI < 0.5. However, this range can be extended to include the dry sub-humid climate type by setting a more conservative value of AI < 0.65.

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References

Abdel Ati, H.A., 1988. The process of famine: causes and consequences in Sudan. Dev. Change 19 (2), 267–300.
Agnew, C.T., 1989. Sahel drought: meteorological or agricultural? Int. J. Climatol. 9 (4), 371–382.
Ahmed, S.H., Abdelhadi, A.W1., Elhadi, M.A., Adam, H.A., 2007. Water requirements of the main crops in the Gezira Scheme. Sudan J. Agric. Res. 9, 67–89.
Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration -guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 300.
Ayoub, A.T., 1999. Land degradation, rainfall variability and food production in the Sahelian zone of the Sudan. Land Degrad. Dev. 10, 489–500.
Baltensperger, D.D., 2002. Progress with proso, pearl and other millets. In: Janick, J., Whipkey, A. (Eds.), Trends in new crops and new uses. ASHS Press, Alexandria, VA, pp. 100–103.
Batterbury, S., Warren, A., 2001. The African Sahel 25 years after the great drought: assessing progress and moving towards new agendas and approaches. Global Environ. Change 11, 1–8.
Bin, H.E., Aifeng, L., Jianjun, W.U., Lin, Z., Ming, L., 2011. Drought hazard assessment and spatial characteristics analysis in China. J. Geogr. Sci. 21 (2), 235–249.
Birkmann, J., 2007. Risk and vulnerability indicators at different scales: applicability, usefulness and policy implications. Environ. Hazards 7, 20–31.
Blum, A., Sulivan, C.Y., 1985. The comparative drought resistance of landraces of sorghum and millet from dry and humid regions. Ann. Bot. 57 (6), 835–846.
Balogun, O.L., 2011. Sustainable agriculture and food crisis in sub-Sahara Africa. Chapter 20. In: Behnassi, M., Draggan, S., Yaya, S. (Eds.), Global food insecurity: Rethinking agricultural and rural development paradigm and policy. , pp. 283–297.
Brown, M.E., Funk, C.C., 2008. Food security under climate change. Science 319 (5863), 580–581.
Central Bureau of Statistics (CBS), 2008. Statistical Year Book for the Year 2007. Ministry of Cabinet, The Republic of Sudan.
Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., Kassam, A., 2007. Assessing the vulnerability of food crop systems in Africa to climate change. Clim. Change 83, 381–399.
Chen, S.-T., Kuo, C.-C., Yu, P.-S., 2009. Historical trends and variability of meteorological droughts in Taiwan. Hydrol. Sci. J. 54 (3), 430–441.
Chen, H., Guo, J., Zhang, Z., Xu, C.-Y., 2013. Prediction of temperature and precipitation in Sudan and South Sudan by using LARS-WG in future. Theor. Appl. Climatol. 113 (3–4), 363–375.
Collier, P., 2007. Poverty reduction in Africa. Proc. Natl. Acad. Sci. 104 (43), 16763–16768.
Conway, D., Schipper, E.L.F., 2011. Adaptation to climate change in Africa: challenges and opportunities identified from Ethiopia. Global Environ. Change 21, 227–237.
Dai, A., Lamb, P.J., Trenberth, K.E., Hulme, M., Jones, P.D., Xie, P., 2004. The recent Sahel drought is real. Int. J. Climatol. 24, 1323–1331.
Davis, H.R.J., 1991. Development programmes in non-irrigated rainland areas. In: Craig, G.M. (Ed.), The agriculture of the Sudan. Oxford University Press, Oxford, pp. 308–338.
Desanker, P.V., Justice, C.O., 2001. Africa and global climate change: critical issues and suggestions for further research and integrated assessment modeling. Clim. Res. 17, 93–103.
Di Baldassarre, G., Elshamy, M., van Griensven, A., Soliman, E., Kigobe, M., Ndomba, P., Mutemi, J., Mutua, F., Moges, S., Xuan, Y., Solomatine, D., Uhlenbrook, S., 2011. Future hydrology and climate in the River Nile basin: a review. Hydrol. Sci. J. 56 (2), 199–211.
Downing, T.E., Ringius, L., Hulme, M., Waughray, D., 1997. Adapting to climate change in Africa. Mitig. Adapt. Strateg. Glob. Change 2 (1), 19–44.
Edossa, D.C., Babel, M.S., Gupta, A.D., 2010. Drought analysis in the Awash River basin, Ethiopia. Water Resour. Manage. 24, 1441–1460.
Elagib, N.A., 2009a. Assessment of drought across central Sudan using UNEP dryness ratio. Hydrol. Res. 40 (5), 481–494.
Elagib, N.A., 2009b. Improved Ångström coefficients for estimating incoming radiation across Sudan. Sudan Engineering Society Journal 55 (52), 59–70.
Elagib, N.A., 2010a. Trends in intra- and inter-annual temperature variabilities across Sudan. Ambio 39 (5–6), 413–429.
Elagib, N.A., 2010b. Exploratory analysis of rain days in central Sudan. Meteorol. Atmos. Phys. 109 (1–2), 47–59.
Elagib, N.A., 2013. Meteorological drought and crop yield in sub-Saharan Sudan I. J. Water Resour. Arid Environ. 3 (3), 164–171 http://www.psipw.org/attachments/article/341/IJWRAE_2%283%29164-171.pdf
Elagib, N.A., Elhag, M.M., 2011. Major climate indicators of ongoing drought in Sudan. J. Hydrol. 409 (3–4), 612–625.
Elagib, N.A., Mansell, M.G., 2000. Climate impacts of environmental degradation in Sudan. GeoJ 50 (4), 311–327.
Elagib, N.A., Alvi, S.H., Mansell, M.G., 1999. Correlationships between clearness index and relative sunshine duration for Sudan. Renew. Energy 17 (4), 473–498.
Elramlawi, H.R.Kh., Saeed, A.B., Mohamed, H.I., 2009. Effect of soil surface formation on yield components of maize (*Zea mays* L.) in the north of Gadaref State, Sudan. J. Sci. Technol. 10 (1), 1–16.
Elshamy, M.E., Seierstad, I.A., Sorteberg, A., 2009. Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. Hydrol. Earth Sys. Sci. 13, 551–565.
El-Tom, A.M., 1986. Climate, environment and development in the Sudan. GeoJ 12 (4), 399–402.
FAO, 2011. FAOSTAT. FAO Statistics Division, http://faostat.fao.org/ (accessed 23.11.2011).
FEWS, 2011. FEWS NET Africa Data Portal. http://earlywarning.usgs.gov/fews/africa/
Ghazanfari, S., Pande, S., Hashemy, M., Sonneveld, B., 2013. Diagnosis of GLDAS LSM based aridity index and dryland identification. J. Environ. Manage. 119, 62–172.
Glantz, M.H., Katz, R.W., 1977. When is a drought a drought? Nature 267, 192–193.
Gray, L., Kevane, M., 1993. For whom is the rural economy resilient? Initial effects of drought in western Sudan. Dev. Change 24 (1), 159–176.
Gregory, P.J., 1982. Interaction of shoot and root characteristics in the response of millet to drought. In: Drought Resistance in Crops with Emphasis on Rice. The International Rice Research Institute (IRRI), Manila, Philippines, pp. 135–143.
Hamad, O.E., Ahmed, A.A.S., El Daw, A.K., 1986. Impact of drought on the Gezira Scheme irrigation needs. In: Proceedings of the International Conference on Water Resources Needs and Planning in Drought Prone Areas, Volume 2, December 1986, Khartoum, pp. 921–932.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Appl. Eng. Agric. 1 (2), 96–99.
Hargreaves, G.L., Hargreaves, G.H., Riley, J.P., 1985. Agricultural benefits for Senegal River basin. J. Irrig. Drain. ASCE 111, 113–124.
Heim Jr., R., 2002. A Review of twentieth-century drought indices used in the United States. Bull. Am. Meteorol. Soc. 83 (8), 1149–1165.
Hendrix, C.S., Glaser, S.M., 2007. Trends and triggers: climate, climate change and civil conflict in Sub-Saharan Africa. Polit. Geogr. 26, 695–715.
Hope Sr., K.R., 2009. Climate change and poverty in Africa. Int. J. Sustain. Dev. World Ecol. 16 (6), 451–461.
Hulme, M., 1996. Recent climatic change in the world's drylands. Geophys. Res. Lett. 23 (1), 61–64.
Hulme, M., Doherty, R., Ngara, T., New, M., Lister, D., 2001. African climate change: 1900–2100. Clim. Res. 17, 145–168.
Hultman, N.E., Hassenzahl, D.M., Rayner, S., 2010. Climate risk. Ann. Rev. Environ. Resour. 35, 283–303.
Hyden, G., 2007. Governance and poverty reduction in Africa. Proc. Nat. Acad. Sci. U.S.A. 104 (43), 16751–16756.
Ibrahim, F.N., 1988. Causes of the famine among the rural population of the Sahelian zone of the Sudan. GeoJ 17 (1), 133–141.
Ingram, J.S.I., Gregory, P.J., Izac, A.-M., 2008. The role of agronomic research in climate change and food security policy. Agric. Ecosyst. Environ. 126, 4–12.
JISAO, 2013. Joint Institute for the Study of the Atmosphere and Ocean, http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml (accessed 30.03.2013).
Kallis, G., 2000. Droughts. Ann. Rev. Environ. Resour. 33, 85–118.
Keyantash, J., Dracup, J.A., 2002. The quantification of drought: an evaluation of drought indices. Bull. Am. Meteorol. Soc. 83 (8), 1167–1180.
Kumar, K., 1998. An early warning system for agricultural drought in an arid region using limited data. J. Arid Environ. 40, 199–209.
Landsberg, H.E., 1975. Sahel drought: Change of climate or part of climate? Arch. Met. Geophys. Biokl. Series B 23, 193–200.
Lansigan, F.P., de los Santos, W.L., Coladilla, J.O., 2000. Agronomic impacts of climate variability on rice production in the Philippines. Agric. Ecosyst. Environ. 82, 129–137.
Larsson, H., 1996. Relationships between rainfall and sorghum, millet and sesame in the Kassala Province, eastern Sudan. J. Arid Environ. 32, 211–223.
Lei, Y., Wang, J., Luo, L., 2011. Drought risk assessment of China's mid-season paddy I. J. Disaster Risk Sci. 2 (2), 32–40.
Li, Y., Ye, W., Wang, M., Yan, X., 2009. Climate change and drought: a risk assessment of crop-yield impacts. Clim. Res. 39, 31–46.
Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science 333, 616–620.
Ministry of Agriculture and Forestry (MAF), 2006. Time series of cropped areas and yield according to the States and irrigation methods (1970/71–004/05). General Administration of Planning and Agricultural Econonomics. Department of Agricultural Statistics.
Mingjun, Z., Jinyun, H., Baolong, W., Shengjie, W., Shanshan, L., Wenli, L., Xuening, M., 2013. Extreme drought changes in Southwest China from 1960 to 2009. J. Geogr. Sci. 23 (1), 3–16.
Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391, 202–216.
Mortimore, M., 2010. Adapting to drought in the Sahel: lessons for climate change. WIREs Clim. Change 1, 134–143.
Munemoto, M., Tachibana, Y., 2012. The recent trend of increasing precipitation in Sahel and the associated inter-hemispheric dipole of global SST. Int. J. Climatol. 32, 1346–1353.
Nastos, P.T., Polito, N., Kapsomenakis, J., 2013. Spatial and temporal variability of the aridity index in Greece. Atmos. Res. 119, 140–152.
Nicholls, N., 1997. Increased Australian wheat yield due to recent climate trends. Nature 387, 484–485.
Nicholson, S.E., 1985. Sub-Saharan rainfall 1981–84. J. Clim. Appl. Meteorol. 24 (2), 1388–1391.
Nicholson, S.E., 1993. An overview of African rainfall fluctuations of the last decade. J. Clim. 6, 1463–1466.
Nicholson, S.E., Davenport, M.L., Malo, A.R., 1990. A comparison of the vegetation response to rainfall in the Sahel and east Africa, using normalized difference vegetation index from NOAA AVHRR. Clim. Change 17, 209–241.
Niemeijer, D., 1998. Soil nutrient harvesting in indigenous teras water harvesting in eastern Sudan. Land Degrad. Dev. 9 (4), 323–330.
Oguntoyinbo, J.S., 1981. Climatic variability and food crop production in West Africa. GeoJ 5 (2), 139–149.
Olsson, L., Eklundh, L., Ardö, J., 2005. A recent greening of the Sahel—trends, patterns and potential causes. J. Arid Environ. 63 (3), 556–566.
Pretty, J., Toulmin, C., Williams, S., 2011. Sustainable intensification in African I. J. Sustain. Agric. 9 (1), 5–24.
Quiring, S.M., 2009. Monitoring drought: an evaluation of meteorological drought indices. Geogr. Compass 3 (1), 64–88.
Sahin, S., 2012. An aridity index defined by precipitation and specific humidity. J. Hydrol. 444–445, 199–208.
Shahid, S., Behrawan, H., 2008. Drought risk assessment in the western part of Bangladesh. Nat. Hazards 46, 391–413.
Silva, V.P.R., 2004. On climate variability in Northeast of Brazil. J. Arid Environ. 58 (4), 575–596.
Sivakumar, M.V.K., 1992. Climatic change and implications for agriculture in Niger. Clim. Change 20, 297–312.
Some'e, B.S., Ezani, A., Tabari, H., 2013. Spatiotemporal trends of aridity index in arid and semi-arid regions of Iran. Theor. Appl. Climatol. 111, 149–160.
Sulieman, H.M., Elagib, N.A., 2012. Implications of climate, land-use and land-cover changes for pastoralism in Eastern Sudan. J. Arid Environ. 85, 132–141.
Sun, L., Mitchell, S.W., Davidson, A., 2012. Multiple drought indices for agricultural drought risk assessment on the Canadian prairies. Int. J. Climatol. 32 (11), 1628–1639.
Tabaria, H., Aghajanloo, M.-B., 2013. Temporal pattern of aridity index in Iran with considering precipitation and evapotranspiration trends. Int. J. Climatol. 33, 396–409.
Tabor, J.A., 1995. Improving crop yields in the Sahel by means of water-harvesting. J. Arid Environ. 30 (1), 83–106.
Tanaka, M., Weare, B.C., Navato, A.R., Newell, R.E., 1975. Recent African rainfall patterns. Nature 255 (5505), 201–203.
Temesgen, B., Allen, R.G., Jensen, D.T., 1999. Adjusting temperature parameters to reflect well-watered conditions. Journal of Irrigation and Drainage Engineering 125 (1), 26–33.
Thomas, A., 2008. Development and properties of 0.25-degree gridded evapotranspiration data fields of China for hydrological studies. J. Hydrol. 358, 145–158.
Thompson, L.M., 1975. Weather variability, climatic change, and grain production. Science 188, 535–541.
Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38 (1), 55–94.
Trilsbach, A., Hulme, M., 1984. Recent rainfall changes in central Sudan and their physical and human implications. Trans. Inst. Br. Geogr. 15, 280–298.
Tsakiris, G., 2007. Practical application of risk and hazard concepts in proactive planning. Eur. Water 19 (20), 47–56.
UNEP, 1992. World Atlas of Desertification. Edward Arnold, London/New York/Melbourne/Auckland.
UNESCO, 1977. Map of the World Distribution of Arid Regions. MAB Technical Notes 7. United Nations Educational, Scientific and Cultural Organization, Paris.
Vasiliades, L., Loukas, A., Liberis, N., 2011. A water balance derived drought index for Pinios River Basin, Greece. Water Resour. Manage. 25, 1087–1101.
Webb, P., Braun, J.V., Teklu, T., 1991. Drought and famine in Ethiopia and Sudan: an ongoing tragedy. Nat. Hazards 4, 85–86.
Wilhite, D.A., 2000. Drought preparedness and response in the context of sub-Saharan Africa. J. Contingen. Crisis Manage. 8 (2), 81–92.
Wilhite, D.A., Glantz, M.H., 1985. Understanding the drought phenomenon: the role of definitions. Wat. Int. 10 (3), 111–120.
World Meteorological Organization, 2006. Drought Monitoring and Early Warning: Concepts, Progress and Future Challenges. WMO - No. 1006, 24.
Wolfe, S.A., 1997. Impact of increased aridity on sand dune activity in the Canadian Prairies. J. Arid Environ. 36, 421–432.
Zhang, J., 2004. Risk assessment of drought disaster in the maize-growing region of Songliao Plain, China. Agric. Ecosyst. Environ. 102, 133–153.
Zhuguo, M., Congbin, F., 2003. Interannual characteristics of the surface hydrological variables over the arid and semi-arid areas of northern China. Global Planet. Change 37, 189–200.