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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.

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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

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

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

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