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Drought versus flood: What matters more to the performance of Sahel farming systems?

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Abstract

Recent climate change has brought new patterns of extreme events in terms of both drought and heavy rainfall to the drought-prone African Sahel. The effects of these recent extreme events on the performance of the Sahel farming systems are still weakly investigated. This study aims at assessing effects of droughts versus floods on crop yield levels and losses, focusing on the so-called recovery period, particularly 2001–2020. A newly developed productivity-drought condition index (PDCI) is utilized to assess agricultural productivity as related to drought or flood in a highly vulnerable region, that is, the Sudanese Sahel. Four farming systems, namely traditional rainfed, mechanized rainfed, gravity irrigated and spate irrigated systems, with sorghum and millet as staple food crops, are considered. The PDCI is defined as a function of the integrated normalized difference vegetation index (iNDVI) over the growing season. To address temporal and spatial variabilities, scaling of the PDCI is done in two dimensions: space and time. Crop statistics are used to derive yield losses. Our results show that both drought and flood episodes (seven and six episodes, respectively) can be captured using the PDCI. Drought remains the most relevant risk to Sahel's crop productivity. Some recent large-scale floods led to yield loss. However, floods cause smaller risks to agricultural productivity compared to droughts. Floods may even result in enhanced crop yields. Based upon scaling in the time or space domain, ranking the severity of drought impacts on crop yield for individual years from 2001 to 2020 reveals least to slightly different results. Vulnerability to drought depends on the crop type and farming system. Drought effect on crop yield from the irrigated sector is clear on individual years but not as a general statistical relationship. The parameter 'percentage area under drought' explains around one-third of the variation in the rainfed crop yield. The spate irrigation scheme, the gravity

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irrigated system and the rainfed farmlands experienced respectively 87%, 57% and 46% of area under drought on average. Irrigated systems produce much higher crop yields than rainfed systems. The mechanized system is more drought-vulnerable than the traditional system. These results call for identifying agricultural management pathways that recognize the combined implications of both hydrological extremes for the region's food security.

KEYWORDS

drought, farming system, flood, normalized difference vegetation index, performance, productivity-drought condition index, Sahel, yield loss

1 | INTRODUCTION

Droughts and floods are hydrological extremes that occur at the two tails of the hydrological spectrum. Both extremes are projected to increase in frequency in the 21st century across many regions of the globe (Hirabayashi et al., 2008). Since they operate on different spatial and temporal scales, their driven impacts have the potential to be felt upon different earth systems and societies. Droughts and floods can lead to disruption of agricultural production and ultimately to food insecurity (Devereux, 2007). Highly drought-prone and food insecure regions are particularly threatened by the multi-faceted features of droughts. Lack of atmospheric supply (rainfall) relative to atmospheric demand (potential evapotranspiration) puts crops at risk from moisture stress and, consequently, reduces crop yield (Elagib, 2014, 2015). Floods disrupt infrastructure (e.g., roads) and may inundate and destroy farmlands, similarly leading to yield loss and jeopardizing household food security (Atanga & Tankpa, 2021; Elagib, Al Zayed, et al., 2021; Oppenheimer et al., 2014). Although the majority of investigations focus on drought effects in the agriculture sector, more studies with a higher spatial resolution are needed especially in regions suffering from a high drought risk (Blauhut, 2020). Ward et al. (2020) noted that addressing both extremes together is needed to design measures and strategies for risk reduction.

To develop sustainable and efficient risk management strategies related to agriculture, it is thus essential to understand the temporal and spatial changes of impacts of drought and flood together. However, lack of both, data and commonly accepted approaches, represents the main obstacle to scientific advancement in the development of performance-oriented management in connection to droughts and floods (Davenport et al., 2015; Elagib, 2015; Jayanthi et al., 2014; Kreibich et al., 2019). For instance, irrigation supply indices assess the delivery performance of irrigation water in the scheme (Kloezen & Garces-Restrepo, 1998; Malano & Burton, 2001). Their application, however, requires extensive data on elements that are either difficult or expensive to measure such as actual evapotranspiration or crop water requirement. Furthermore, changes in patterns of only annual precipitation, heavy precipitation or differences between precipitation and evapotranspiration cannot explain changes in flood and drought (Hirabayashi et al., 2008). Rather than merely focusing on drought drivers, i.e. lack of precipitation (meteorological), lack of soil water (agricultural), and lack of runoff (hydrological) droughts, a paradigm shift toward analyzing drought impacts is promoted (Blauhut et al., 2015, 2016; Kchouk et al., 2022; Walker, 2022). Increasing availability of new observational datasets, particularly those based on remote sensing techniques, have the potential of augmenting scarce and dispersed ground-based observations to facilitate analysis of drought at multiple scales (e.g., spatial and temporal). Improved accessibility of remote sensing data provides a good basis to develop performance indicators, especially to diagnose large-scale irrigation schemes (Al Zayed et al., 2015; Al Zayed & Elagib, 2017; Bastiaanssen & Bos, 1999; Hamid et al., 2011).

The overall objective of this study is to improve our understanding of the relative or compound effect of climate variability on agricultural yield. In this article, we hypothesize that drought and flood characteristics in space or in time dimension differ significantly in terms of severity, timing of occurrence and effect. Therefore, the above overall objective is split into three:

1. To devise an index that accounts for characterization of dryness and wetness both in space and in time dimensions by which the performance of farming systems can be captured, especially in terms of effects on farm productivity.
2. To quantify the magnitude of crop yield loss due to the effects of both drought and floods.
3. To identify which phenomenon of the two extreme events is more pertinent to crop yield loss.

To achieve the above research objectives, the interest of the study is on the case of the Sahel zone of Sudan. The African Sahel is a unique example of vulnerable regions to both hydrological extremes in the recent history. Severe and protracted droughts plagued the region during the 1970s and 1980s (Hulme, 2001; Kerr, 1985; Tanaka et al., 1975). It is now over a quarter of a century since the Sahel drought, which began in the late 1960s and peaked in the 1980s, has ended (Ali & Lebel, 2009; Lebel & Ali, 2009; Nicholson, 2005). However, the return to wetter conditions was more pronounced in the eastern Sahel than in the western part (Ali & Lebel, 2009; Lebel & Ali, 2009; Nicholson, 2014; Nicholson et al., 2018). Despite this recovery of Sahel rainfall, studies have reported increased spatiotemporal rainfall variability in recent years (e.g., Ali & Lebel, 2009; Lebel & Ali, 2009; Sulieman & Elagib, 2012). On one hand, several regional and/or local drought crises did occur despite the ample signs of rainfall recovery and re-greening (Bégué et al., 2011; Elagib & Elhag, 2011; Herrmann et al., 2005; Olsson et al., 2005). On the other hand, researchers concluded that the higher amounts of annual rainfall and river flows are due to more intense rainfall rather than more frequent rain events (Casse & Gosset, 2015; Descroix et al., 2012; Elagib, Al Zayed, et al., 2021; Elagib, Saad, et al., 2021; Ly et al., 2013; Panthou et al., 2014; Panthou et al., 2018; Taye & Willems, 2012; Wilcox et al., 2018).

Except in scattered areas across the Sahel, Elagib and Elhag (2011) and Porkka et al. (2021) yet refuted that the recent increases in annual rainfall are an improvement in rainfall characteristics that are relevant to agriculture. Examining the performance of Sahel agricultural systems requires an agricultural definition of drought. Meteorological definitions of Sahel drought are not sufficient to address agricultural impacts (Agnew, 1989). Kchouk et al. (2022) recommended shifting the focus from deficit of water volumes and flows towards considering the human welfare and societally relevant aspects (e.g., food and water securities) affected by droughts. This focus in defining drought explains the emphasis on agricultural drought and food security indices for Sub-Saharan Africa (Kchouk et al., 2022). The people in the Sahel of Sudan used to identify drought by its impact using indices such as annual crop production (Abu Sin, 1986). One-third of the communities in Sub-Saharan Africa are adversely affected by recurrent droughts, accounting for example for 11.8% of agricultural gross domestic product losses over the period 1999–2000 in Eastern Africa alone (Bedeke, 2023). Since the majority of the inhabitants of the Sahel are involved in agriculture, the impacts of climate vagaries on Sahel dryland farming should provide the basis for assessing agricultural droughts (Abu Sin, 1986; Agnew, 1989). In contrast, flood as a hazard in the Sahel is comparably less investigated than drought (Ayanlade et al., 2022; Elagib, Al Zayed, et al., 2021; Epule et al., 2018; Tarhule, 2005; Tschakert et al., 2010). Modelling approaches showed that ~12% of the people across rural areas in Sub-Saharan Africa experienced food insecurity from 2009 to 2020 due to flooding (Reed et al., 2022). The above literature review raises the question as to how the recovery of Sahelian precipitation amount with its increasing variability has affected agricultural yield. Attempts have been made to examine the performance of irrigated farming systems based only on the assessment of water supply (water distribution and irrigation adequacy) and plant water demand (Fadul et al., 2020; Ghebreamlak et al., 2018). These approaches, however, do not link this supplied water amount explicitly to the crop productivity. Moreover, lack of detailed and consistent record of crop statistics is quite relevant here (Davenport et al., 2015; Jayanthi et al., 2014).

2 | MATERIALS AND METHODS

2.1 | Study area

Given its representation of one-third of the total area of the African Sahel region, this study focused on the case of the Sudanese Sahel in the eastern part of the region. The Sahel in Sudan (Figure 1) was considered an appropriate choice for several reasons. This region is characterized by arid and semi-arid environments encompassing ~1 million km^2. It is known to accommodate the main four agricultural farming systems of the greater Sahel region: rainfed traditional, rainfed (semi-)mechanized, gravity-irrigated and spate-irrigated systems. Gravity irrigation is due to surface irrigation depending on the Nile River whereas spate irrigation is done by managing (unpredictable) flash floods. Traditional rainfed farming is characterized mostly by smallholdings, labour intensive operation and use of hand tools. Mechanized rainfed farming is practiced by individual big farmers and companies (CFSAM, 2011; UNEP, 2007) employing typically very selective mechanized operations (El-Dukheri et al., 2011; Shepherd, 1983). The irrigation sector is composed of small to medium-scale mechanized or large-scale commercial farms fed by gravity irrigation or water pumping from the Nile River and its tributaries (CFSAM, 2011; Hamid et al., 2011). This sector comprises the most extensive irrigated area in Sub-Saharan Africa (Mahgoub, 2014). Despite the great potential of the country for sufficient and sustainable agricultural production, it has generally gone untapped (Laki, 1994) with the total arable land under cultivation only estimated to be 21% (El-Dukheri et al., 2011).

Within this area, there are mainly five irrigation schemes for crop cultivation (Figure 1). The total irrigated land in this region (e.g., sorghum) is usually small, ranging from 3% to 10% with an average of 7% (Elagib, 2014). Thus, food security in the Sahel part of Sudan relies heavily on production in the rainfed agriculture sector.

2.2 | Data and processing

As pointed out in the introduction, the Sahel region is inherent with lack of extensive spatial and temporal data. This study focuses on the period 2001–2020 for two reasons, first to consider the recovery period and second to make use of available remote sensing data. For the present multi-year analysis, an annual land use/land cover is needed. The global HIstoric Land Dynamics Assessment (HILDA+) has six land-use categories, namely Urban areas, Cropland, Pasture/rangeland, Forest, Unmanaged grass/shrubland, Sparse/no vegetation, with a resolution of 1 km over the period 1960–2019 (Winkler et al., 2021). This research thus extracted the cropland as the land use of the interest from Winkler et al. (2020). Since the HILDA+ dataset spans only until 2019, the cropland area of the year 2020 was assumed to remain as that in the year 2019. Dekadal data on NDVI were obtained from the Moderate Resolution Imaging Spectroradiometer (eMODIS NDVI collection 6). The spatial resolution of eMODIS NDVI data is 250 m. The retrieved datasets cover the period from 2001 through 2020. The NDVI data has been used for long in Sahel drought and vegetation monitoring (e.g., Anyamba & Tucker, 2005; Malo & Nicholson, 1990; Tucker et al., 1986).

Finally, crop statistics on planted area, harvested area and production for the period were acquired from different sources. Although the focus of the present analysis is on the period 2001–2020, acquisition of crop statistics of longer time series (herein since 1970) was necessary to facilitate a pre-requisite analysis as will be described in

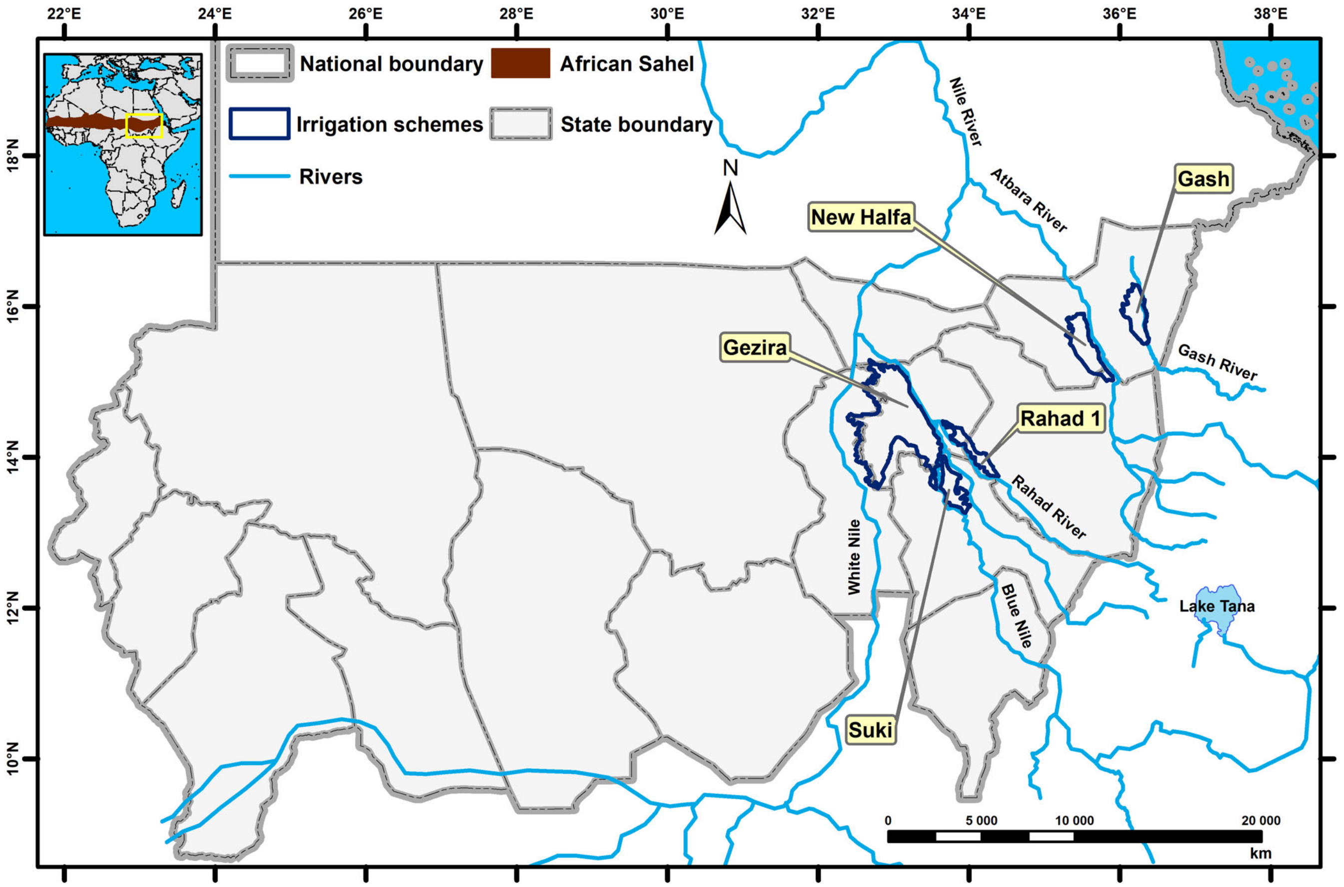

FIGURE 1 Sahel zone of Sudan and main irrigation schemes: gravity irrigation (Gezira, Rahad 1, Suki, New Halfa) and spate irrigation (Gash). Rainfed croplands expand across the region and vary according to the local environmental conditions both spatially and temporally. Thus, the rainfed cropland is not shown here.

Section 2.4. The data for the period 1970–2004 were compiled from the statistical yearbooks of the Ministry of Agriculture and Forests (MAF, 2006) and the Central Bureau of Statistics (CBS, 2008) of Sudan. These data were also augmented until 2020 from the Department of Agricultural Statistics, General Administration of Planning and Agricultural Economics, Ministry of Agriculture and Natural Resources of Sudan. Two crops were considered here, that is, sorghum and millet, because they are the most important staple food crops. Both crops are grown during the rainy season and the period of high river flows (mainly July to October). However, millet is not cultivated in the irrigated schemes under study. To obtain the Sahel-wide sorghum or millet data, the data on production and planted area that were originally provided for each state of the Sudanese Sahel were summed up. The yield per hectare for a given crop was obtained by dividing the total Sahel crop production by the total Sahel harvested area.

2.3 | Development of a drought index

Kogen (1990); Kogan (1995) and Kogan and Sullivan (1993) derived the vegetation condition index (VCI), as a state indicator for the vegetation state, based on the smoothed weekly NDVI. The VCI was calculated using multi-year maximum ($NDVI_{max}$) and minimum NDVI ($NDVI_{min}$) of each grid cell and the maximum composite over a week by the following expression:

$$VCI = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \times 100\% \quad (1)$$

In the above studies, NDVI was used for each grid cell and week. The VCI was linearly scaled from 0% to 100%, corresponding to $NDVI_{min}$ and $NDVI_{max}$, respectively. Low values of VCI describe poor vegetation conditions in the respective year which is most often the result of unfavourable weather conditions, while high values refer to the opposite situation of vegetation and thus weather.

Since our study is concerned about the performance of the different farming systems due to the effects of droughts versus floods, connecting productivity of the different farming systems to these extreme events is pertinent. It follows that the use of a productivity index obtained by summing up the original dekadal NDVI images over the entire growing season is meaningful and more appropriate here for capturing this performance. The integrated NDVI (iNDVI) is widely accepted and used to approximate vegetation productivity in studies dealing with detection of trends and patterns of drought and regreening in the Sahel (Elagib, Khalifa, et al., 2021; Malo & Nicholson, 1990; Nicholson et al., 1990; Olsson et al., 2005). A seasonal NDVI dataset was, therefore, compiled over the growing season that is, June to October, for each NDVI grid cell similar to previous studies for the region (Elagib et al., 2019; Khalifa et al., 2018). This data stack was then used to produce the iNDVI datasets for the growing season. Against the assumption that within an irrigation scheme, water availability should be ideally sufficient and equitable, the iNDVI is expected to show little variation within the same land use or climate zone or over time (Al Zayed & Elagib, 2017; Khalifa et al., 2020). This situation is not the case in rainfed agriculture (Elagib, 2014; Elagib et al., 2019; Elagib, Khalifa, et al., 2021). Al Zayed et al. (2015) used iNDVI in place of NDVI in Equation (1) to propose a modified VCI to monitor the spatial efficiency of water distribution in the large-scale Gezira Irrigation Scheme in Sudan. Our present study takes this proposal further to derive a productivity-drought condition index (PDCI) for each pixel within the Sahel region by applying the following formula:

$$\mathrm{PDCI} = \frac{\mathrm{iNDVI} - \mathrm{iNDVI}_{\min}}{\mathrm{iNDVI}_{\max} - \mathrm{iNDVI}_{\min}} \times 100\%, \tag{2}$$

where iNDVI is the summed dekadal NDVI value over the rainy season and iNDVI_{max} and iNDVI_{min} are the maximum and the minimum iNDVI, respectively. Equation (2) was used to calculate PDCI in two dimensions, namely space (PDCIs) and time (PDCIt), based on maximum and minimum iNDVIs for each dimension. In the former dimension, the extreme iNDVI values were detected areally for each year. PDCIs therefore shows spatial patterns of differences in crop productivity under water stress/abundance. In the time dimension, the extreme iNDVIs were detected in the 20-year time series of each grid. Therefore, PDCIt shows patterns of inter-annual variability of crop productivity in a drought or flood year. The normalization performed by Equation (2) yields a range of PDCI value from 0% to 100%. The PDCIs is more powerful in displaying the heterogeneity in performance in space within the same farming system (Al Zayed et al., 2015; Elagib et al., 2019).

With this background, we thus hypothesize that the spatial and temporal patterns can be explained to some part by the management system. To calculate the PDCI, we differentiated between irrigated and rainfed croplands on the scale of the entire Sudanese Sahel region. For irrigated croplands, we used two sets of iNDVI extremes: (i) extremes defined for all gravity irrigated schemes together (Gezira, Suki and Rahad 1) and (ii) local extremes for the spate irrigated scheme (Gash) alone. The reason for this treatment was the differential of systems of irrigation between the two. As for the rainfed croplands, we used unified iNDVI extreme values throughout the region. Here, we assumed that all croplands outside the main irrigation schemes are rainfed. This might lead to a systematic underestimation of the effects of small-scale irrigation farms within the system of rainfed agriculture and it might lead to uncertainties in assessing the temporal and spatial patterns within this class. However, it is the only

TABLE 1 Classification of the productivity-drought condition index (PDCI).

Drought	PDCI value (%)
Extreme	0 ≤ PDCI < 10
Severe	10 ≤ PDCI < 20
Moderate	20 ≤ PDCI < 30
Mild	30 ≤ PDCI < 40
No drought	PDCI ≥ 40

reproducible approach as data on small-scale irrigation is unavailable and to our experience varies largely temporally and spatially.

For any given farming system under study, the PDCIs was calculated for each year and pixel within the farming system according to Equation (2). Thus, the PDCIs shows the spatial variability of the drought-relate productivity within each farming system (gravity irrigated, spate irrigated, rainfed) and therefore yields a value per year and pixel. Interannual variabilities in the PDCIs is expected to reduce strongly or even be masked for the reason that the PDCIs derived the maximum and minimum values of iNDVI from the spatial domain for each year separately. The PDCIt, however, was calculated using the mean value of iNDVI over all pixels of a given farming system and therefore yields a value per year and farming system. Thus, the PDCIt value refers to the temporal variability of the productivity within a farming system. When normalizing the PDCI according to time, the time series of PDCIt thus clearly distinguishes dry and wet years.

The drought severity for a given productivity defined by PDCIs or PDCIt was classified in analogy to the moisture-stress scheme proposed by Bhuiyan et al. (2006, 2017), thus categorizing drought from extreme to no drought, as shown in Table 1. Finally, this classification was used to map the different drought and non-drought areas for each farming system.

2.4 | Analysis of crop yield

Analysing the magnitude of crop yield loss due to drought and assessing the performance of different agricultural systems are important for assessing risks to agricultural production. Studying the hazard alone does not suitably reflect impacts and possible pathways for adaptation. Removing the effect of non-climatic factors from the crop yield data is a usual procedure in climate-related analysis (Nicholls, 1997; Lobell et al., 2011; Agnew, 1989; Li et al., 2009). Some researchers only removed the linear trend from the yield data (e.g., Zhang, 2004; Li et al., 2009; Sun et al., 2012). Instead, Elagib et al. (2019) proposed identifying breakpoints (years) in the time series first. This approach is essential since yield changes often do not follow a linear trend, but are due to regime changes (climate, management, etc), which can be sudden and stepwise. They used the regime shift detection technique proposed by Rodionov (2004) with a cut-off length of 10 years to allow separation of short-term climate variability from long-term trends. In this study, we followed the suggestion put forward by Elagib et al. (2019) for de-trending the entire sorghum and millet yield time series. The trend was then deducted from the actual yield time series of each regime to analyse the residuals, of which the negative residuals were of interest as yield losses. Finally, these yield losses were normalized by the linear trend for each regime. These steps are explained by the following equations:

$$Y_{ti} = a + bX_i \tag{3}$$

$$YL_i = Y_{ai} - Y_{ti} (\text{for yield losses only, i.e., when } Y_{ai} \leq Y_{ti}) \tag{4}$$

$$YL_{ni} = \frac{YL_i}{Y_{ti}} \times 100 \tag{5}$$

Equation (3) expresses the linear trend of actual yield during the given regime where Y_{ti} is the expected yield at year i, a is the y-intercept, b is the slope and X_i is the year i; Equation (4) obtains the residuals of yield representing yield losses during the given regime where YL_i is the yield loss and Y_{ai} is the actual yield at the year i; Equation (5) normalizes the yield losses calculated using Equation (4) where YL_{ni} is the normalized yield loss in %.

2.5 | Analysis of the performance of farming systems

We assume that sustainable recovery from drought in the Sahel requires resilient and sufficiently productive farming systems. Therefore, the assessment of the performance of different farming systems requires accounting for sensitivity of yield levels to drought conditions. The relationship between change of yield level and drought was investigated using the following three null-hypothesis, using a two-tailed test of the significance of the correlation factor.

i. There is no relationship between temporal and/or spatial patterns of crop yield and drought severity as expressed by the PDCIs or PDCIt index. Thus, the relationship between crop yield and the two drought indices was examined. The goal was to assess the suitability of these two indices to capture impacts of drought severity on the crop yield of a farming system in terms of temporal and spatial characteristics and to refute the null-hypothesis.
ii. No relationship exists between crop yield loss and percentage of drought area. To this end, we also explored the relationship between crop yield and percentage of drought area by using a regression analysis of the crop yield on the percentage of total drought area for each farming system.
iii. Finally, no relationship exists between amount of yield loss and drought severity. To address this null-hypothesis, the amount and year of occurrence of yield levels and losses were determined while characterizing the drought in terms of severity and year of occurrence using the PDCIs and PDCIt.

In addition, we investigated the temporal coherence of drought or flood on one side and consecutive changes in yield on the other side. To this end, the PDCI values were ranked and compared to the ranking of yield levels. This approach was carried out for each farming system and the two crops to address the null-hypothesis that the farming systems do not have an effect upon the change in yield level in response to droughts or floods. Thus, an inter-comparison of the performance of the four different farming systems (gravity irrigation, spate irrigation, rainfed traditional and rained mechanized) was undertaken during the years with yield loss. The significance of the difference between the means of yield or yield loss among the four farming systems was investigated. To this end, we used the Z-test for two population means with known but unequal variances (Kanji, 1997).

2.6 | Trend direction

To examine whether the direction of trends in the PDCIs and PDCIt time series is towards wet or dry conditions, we used the two-tailed non-parametric Kendall tau correlation test (Kanji, 1997). Since climate variability is high in this arid and semi-arid region, we hypothesized that climate-related data such as the PDCI data are not normally distributed. Therefore, a nonparametric test is relevant since it is distribution-free, that is, does not require data meeting the required assumption of normal distribution. Two-tailed test was used since a direction of the trend was not hypothesized. Similarly, the trend in the total drought area within each farming system was examined.

3 | RESULTS

3.1 | Temporal analysis of PDCI

A glance at the PDCIs time series reveals that all cropland types are mostly under drought (Figure 2a). While the gravity irrigated schemes and rainfed croplands are under mild and rarely under no drought conditions, the spate irrigated scheme is mostly under severe or moderate drought. The average performance level of the gravity irrigated schemes and rainfed croplands is just below the borderline of no drought (average is 38.6% and 39.6%, respectively). A PDCIs average of 24.9% is shown for the spate irrigated scheme. The year-to-year variability in the PDCIs is more pronounced in the spate irrigated scheme compared to the other two farming systems. This behaviour is expected because spate irrigation farming system depends on opportunistic floodwater availability generated by highly variable rains from year to year. The larger interannual variability of PDCIs for the spate irrigation scheme indicates larger spatial variability in productivity of this scheme. Each year, there are pixels / locations showing less overall water stress as compared to others within the same scheme. The spatial variability of wetness/dryness and thus productivity in the rainfed and gravity irrigated systems is comparatively small. Drought is typically a large-scale phenomenon. Thus, the PDCIs is particularly useful to assess spatial heterogeneity effects of different

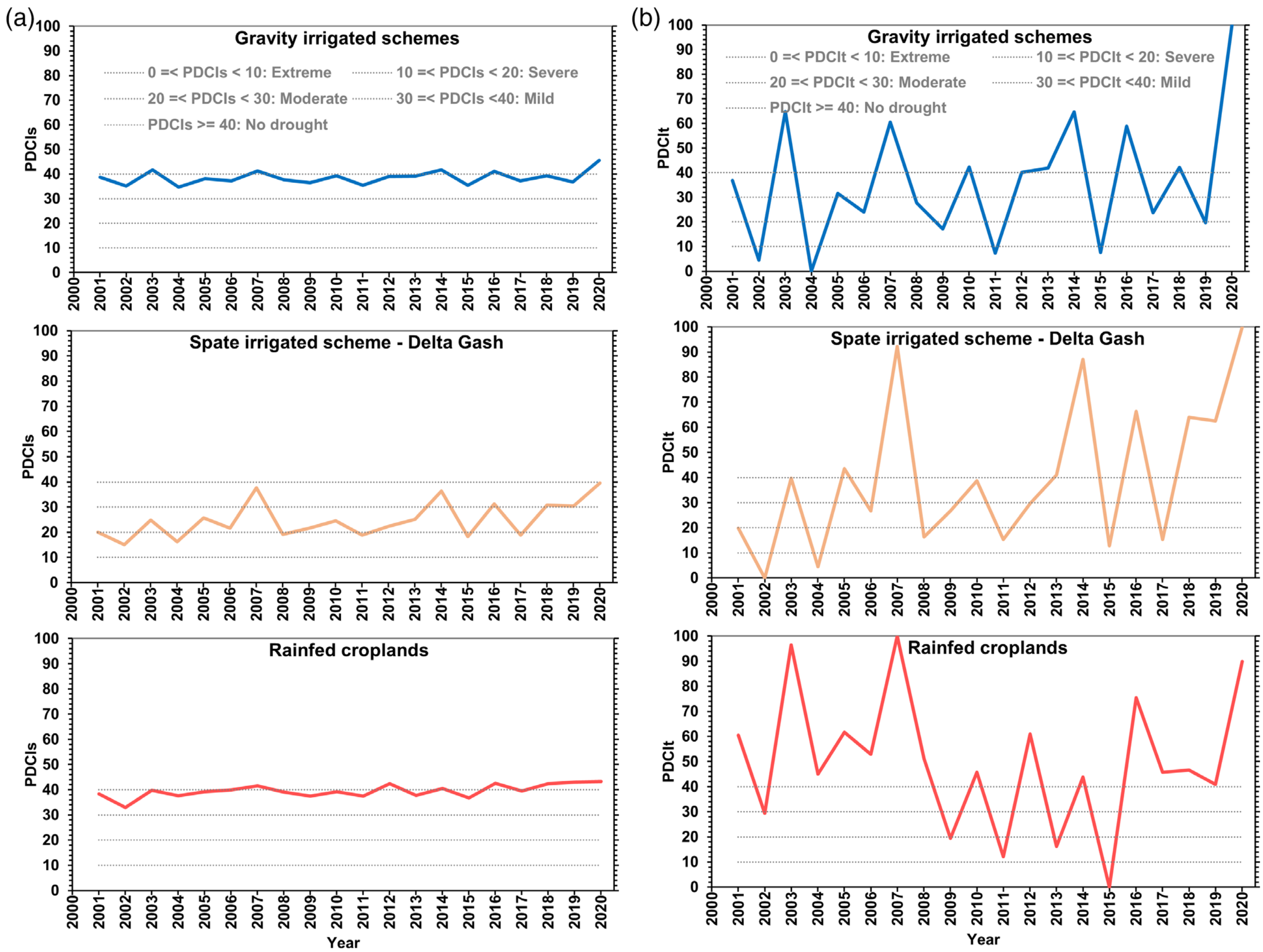

FIGURE 2 Time series and classification of the productivity-drought condition index (PDCI). (a) Space-dependent (PDCIs) and (b) time-dependent (PDCIt).

agricultural management systems. Contrary to the PDCIs, the PCDIt focusses on interannual variability (Figure 2b). Figure 2b shows 5, 9 and 12 drought years during the study period for the rainfed, the gravity irrigation and the spate irrigation systems, respectively.

Despite the differences between the two drought indices, the timing of high and low peaks shows considerably similarities especially in extreme years. Examples of extremely dry years are 2002, 2004, 2011 and 2015. Extremely wet years are exemplified by 2003, 2007, 2016 and 2020. Figure 2a,b do not show any significant trend except a slightly increasing trend of PDCIs for rainfed cropland. In this case, the Kendall Tau test shows a significant increasing trend ($p = 0.014$) towards wetter conditions.

3.2 | Spatial analysis of PDCIs

For rainfed croplands, the spatial pattern indicates areas under severe drought in 2002, 2011, 2015, 2017 and 2019 (Figure 3). Non-drought conditions exist consistently in the eastern part of the region. Among the five irrigation schemes, the Rahad 1 scheme is the most favoured by wet conditions (Figure 4). In contrast, the Gash Delta in the farthest east suffers consistently from severe droughts. Similar to the rainfed sector, the years 2002, 2011, 2015, 2017 and 2019 were strikingly dry even in the irrigated sector. The coincidence of droughts effects in both rainfed and irrigated farming schemes shows the climate vulnerability, which cannot be completely mitigated by irrigation.

Evidence of synchronization of the performances of the various farming system is obvious in Figure 5. Lack of rainfall leads to drought-affected areas in all four types of farming systems. The percentage area under drought for the spate irrigation scheme is particularly large. Being small and particularly vulnerable to erratic and spatially highly variable rainfall events, these characteristics increase the inherent PDCIs heterogeneity in the spate irrigation scheme. Extreme dry years are visible in each of the farming systems indicating the large-scale character and longevity of drought events. Apart from the aforementioned drought years, 2007 and 2014 were common wet years among all the systems. Additionally, prevalent wet conditions in 2003 and 2020 can also be noted for both the gravity-irrigated and rainfed systems.

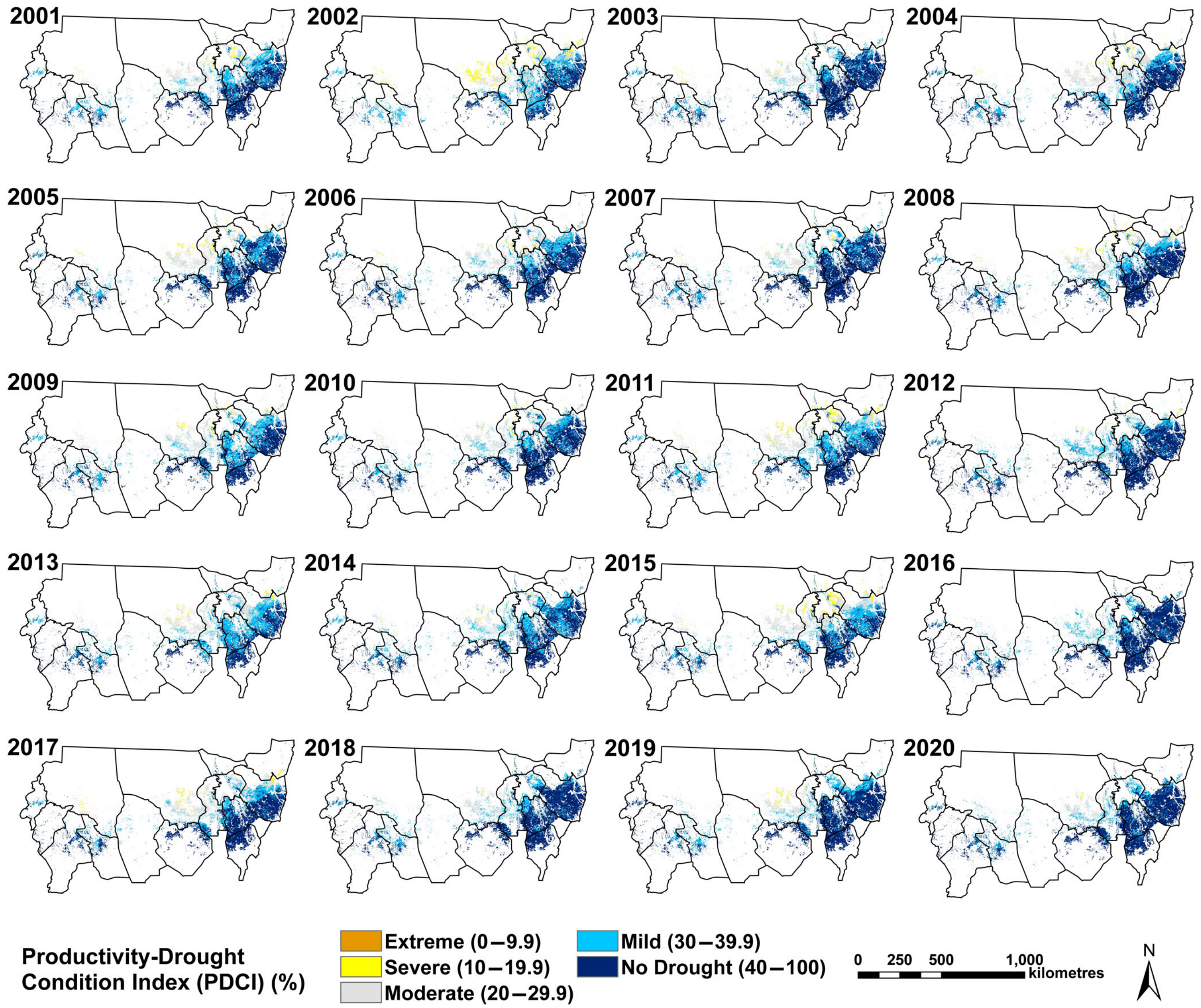

FIGURE 3 Spatial pattern and classification of space-dependent productivity-drought condition index across the rainfed croplands.

On average, 87%, 57% and 46% of the area of the spate irrigation scheme, the gravity irrigated system and the rainfed farmlands was under drought respectively. It is worthwhile noting that these percentages depend upon the magnitude of reference areal $iNDVI_{max}$ and $iNDVI_{min}$ used each year for the given farming system. No significant trend was found in the percentage of total area under drought over the full 20-year period for any of the farming systems. Over the period 2013–2020, however, the rainfed system showed a falling trend significant at $p = 0.026$.

3.3 | How do space and time dimensions of drought affect crop yield?

An insight into how the space and time dimensions of drought affects crop yield in rainfed systems can be gained from the scatter plot of crop yield versus PDCIs and PDCIt (Figure 6). We limited this analysis to rainfed systems since no significant relationship of the PDCI values and the yield level was found for the irrigated systems. As expected, rainfed agriculture is influenced significantly by drought. Yield decreases with increasing drought. For a given crop, drought affects traditional food crop system more than its mechanized counterpart in the space dimension. An increase of 1% in PDCIs leads to an increase in crop yield of about 14.5–29.2 kg/ha. The two limits characterize the mechanized and traditional millet systems, respectively. However, this influence of spatial drought does not differ between the traditional and mechanized sorghum sectors. Both systems show an increase of around 23 kg/ha for a rise of 1% in PDCIs. Within the same sector, traditional millet is affected more by drought in space than traditional sorghum, but the opposite is true for the mechanized systems. The space drought dimension expresses about 27% to 42% of the variation in the yield of mechanized sorghum and traditional millet, respectively. If the extreme yield value (725 kg/ha) for traditional millet was removed, this percentage would increase to 56%

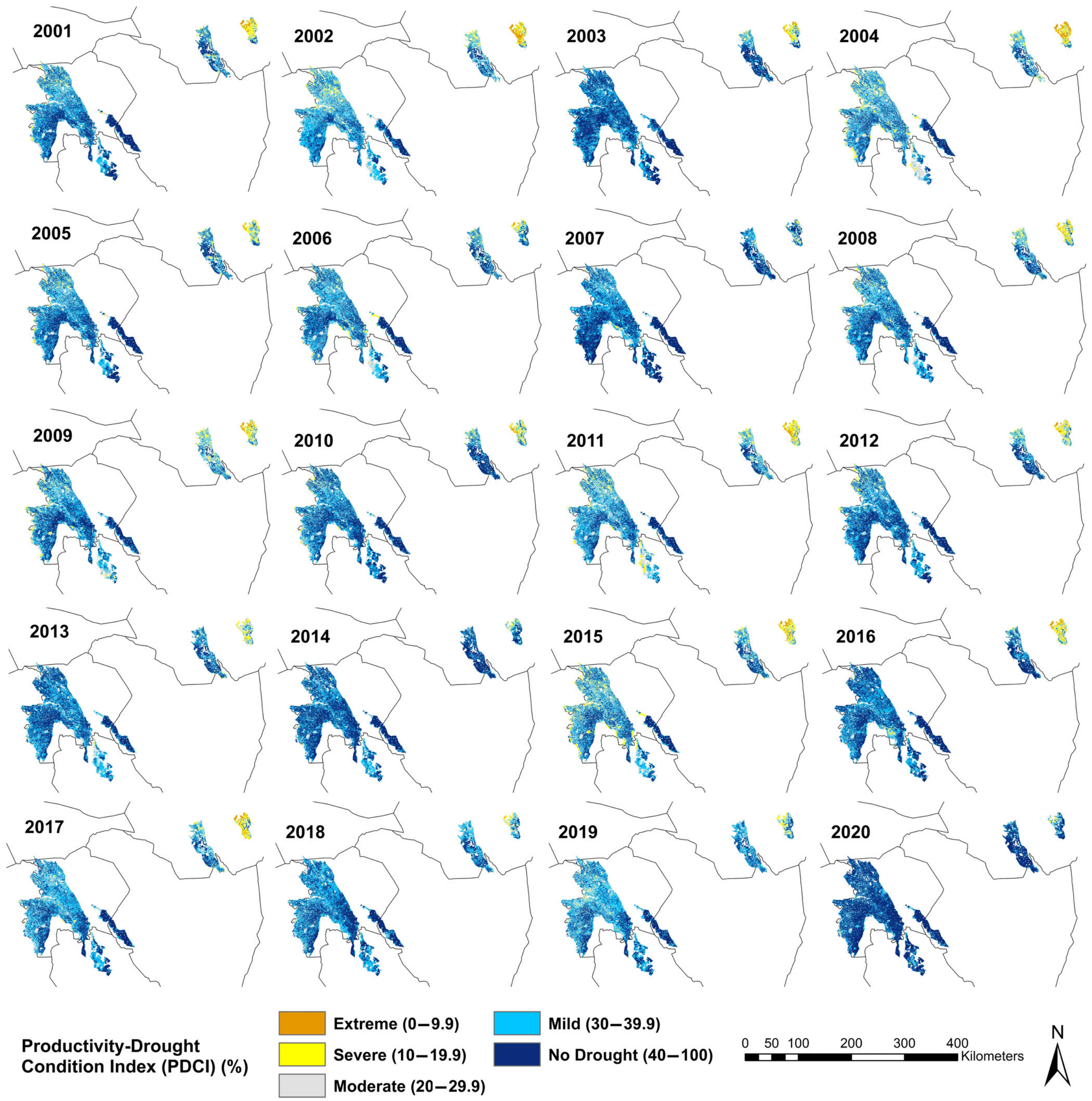

FIGURE 4 Spatial pattern and classification of space-dependent productivity-drought condition index across the irrigated croplands.

($p = 0.0002$). Accordingly, a 1% increase in PDCIs leads to an increase of 21.0 kg/ha in the crop yield. When drought is scaled in time dimension, its effect can only be seen on the mechanized farming system (Figure 6f,h). The other farming systems do not show significant relationships (e.g., traditional systems in Figure 6e,g). Less influence is revealed by time-dependent drought on millet than sorghum. A 1% increase in PDCIt leads to a significant increase in crop yield of only up to 1.2 kg/ha for millet or 2.0 kg/ha for sorghum in the mechanized farming. Additional comparative analysis of the preference of PDCI to iNDVI in explaining the variation in yield favored the PDCIs. The iNDVI explained the same amount of variation in yield as that exhibited by PDCIt but only for the mechanized system (Figure S1). These results provide evidence of the merit of the PDCI index.

Again, the crop yield of the rainfed croplands is highly significantly correlated with the percentage of the total area under drought (Figure 7). All the crop yields vary inversely with drought area. The total area under drought explains around one-third of the variations in the crop yield. During the study period, crop yield declined at a rate of 3.5 to 6.6 kg/ha for each 1% increase in the drought area of mechanized and traditional millet, respectively. If the extreme yield of

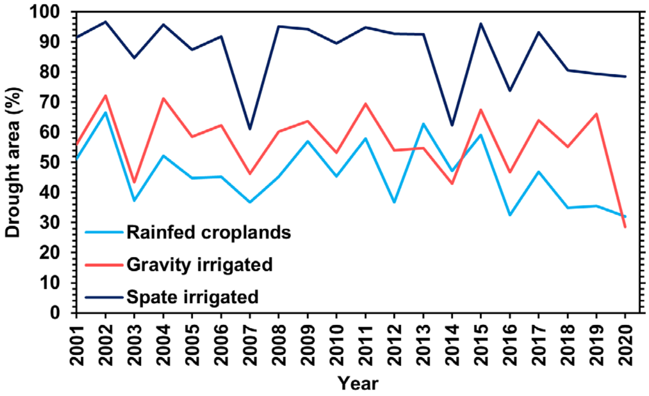

FIGURE 5 Time series of percentage of the total area of the farming systems under drought shown in Figure 3 as measured by space-dependent productivity-drought condition index with a value of 40% or less.

traditional millet was eliminated from the scatter plot, the correlation would give an R^2 of 0.4521 ($p = 0.0016$) and a slope of -4.6 kg/ha. No apparent relationship was found between the sorghum yield and drought area in any of the two irrigated systems.

3.4 | Ranking of drought episodes

Based on the PDCIs, there were 13, 15 and 20 episodes of drought that hit the rainfed, gravity-irrigated and spate-irrigated farming systems, respectively, within the 20-year study period (Figure 8a). Noteworthy is that the years 2002, 2004, 2011 and 2015 were common among the five driest years in all the farming croplands. Among these five most dry years was also 2009 in the rainfed and gravity irrigated systems. Only for the spate irrigated system, the year 2017 was also identified as member of the driest quintile. All the systems except the spate irrigated system (Gash Delta) share 2020 as the wettest year. The years 2019, 2003 and 2007 were the second wettest in the respective farming systems. All the farming systems constantly experienced crop yield loss when PDCIs are ≤39%. Nevertheless, crop yield also occurred in wet years. Except for the rainfed mechanized system, all other farming systems encountered yield loss in the wettest year 2020. The year 2019 was characterized by a widespread crop yield loss in the rainfed sorghum (both traditional and mechanized) and rainfed traditional millet. Out of the five wettest years in the gravity irrigated sector, four underwent sorghum yield loss. Likewise, the spate irrigated sector also experienced sorghum yield loss in the two wettest years 2020 and 2007 though both years still recorded PDCIs of less than 40%.

Based on PDCIt, 5, 11 and 12 drought years occurred during the last two decades, respectively in the rainfed, gravity-irrigated and spate-irrigated farming systems (Figure 8b). However, with the exception of the gravity irrigated scheme, the ranking of the extremely dry or wet years varies between the different farming systems. The five driest episodes are in the order of 2015, 2011, 2013, 2009 and 2002 for the rainfed croplands, 2004, 2002, 2011, 2015 and 2009 for the gravity-irrigated croplands and 2002, 2004, 2015, 2011 and 2017 for the spate irrigated scheme. Figure 8b also indicates that crop yield loss took place in two of the farming systems, namely the rainfed and gravity irrigated systems, continuously from PDCIt ≤41%. This result means that crop yield loss can occur even in a non-drought condition. In the spate irrigated system, yield loss of sorghum happened when PDCIt was ≤15%. This drought index also confirms the occurrence of crop yield loss in extremely wet years. For instance, all the systems witnessed crop yield loss in 2020, except in the rainfed mechanized sector. This exception corroborates the resilience of this system to the extreme wet condition revealed by the PDCIs. However, both rainfed mechanized systems encountered sorghum and millet yield loss in the wet year 2007. This year also recorded sorghum yield loss in the spate irrigated scheme. In addition to 2020, the gravity irrigated scheme underwent sorghum yield loss in the second and third-most wet years, that is, 2003 and 2014, respectively.

3.5 | Ranking of yield levels and losses

The last two decades witnessed several years with yield loss (Figure 9). Three farming systems, namely rainfed traditional sorghum and millet and rainfed mechanized millet, suffered 11 years of crop yield loss. The rainfed mechanized and gravity-irrigated systems experienced sorghum yield loss in 10 years. There were only 7 years with sorghum yield loss in the spate irrigated system. At a first glance, one can see a match between the ranking of years in order of decreasing yield and increasing yield loss for the two rainfed mechanized sectors. The exception to this match is the 3 years with greatest yield losses of mechanized millet. It is almost so for the gravity irrigated system except for the three highest yields (lowest yield losses). This match is not the case for the other farming systems. It is important to interpret Figure 9 in close association with Figure 8. For rainfed sorghum, the lowest three yields and highest yield losses occurred when both PDCIs and PDCIt were at drought levels. This situation is clearly demonstrated in the years 2013, 2009 and 2004 for the traditional system and in 2009, 2011 and 2002 for the mechanized sorghum. The opposite is true for the traditional millet in 2009, 2011 and 2002 when the sector reported the lowest yield losses corresponding to drought levels on the PDCIs scale. The state of mechanized millet is not clear in this regard, as it demonstrates a mixed picture. For example, the year 2015 was the driest on the PDCIt scale and second driest on the PDCIs scale. While this year had the lowest yield, this yield level corresponded to the fourth highest yield loss. Moreover, the year 2002 reported the severest drought on the PDCIs scale and fifth driest condition on the PDCIt scale. The yield was third highest and the yield loss then was third lowest. The gravity-irrigated system was resilient in the driest years (2004 and 2002), thus reporting no yield loss. It was, however, highly vulnerable in a year with borderline drought level (40%) like 2012, thus recording the lowest yield and highest yield loss of sorghum. No sorghum yield loss was reported for the spate irrigated scheme in the driest year (2002), thus revealing

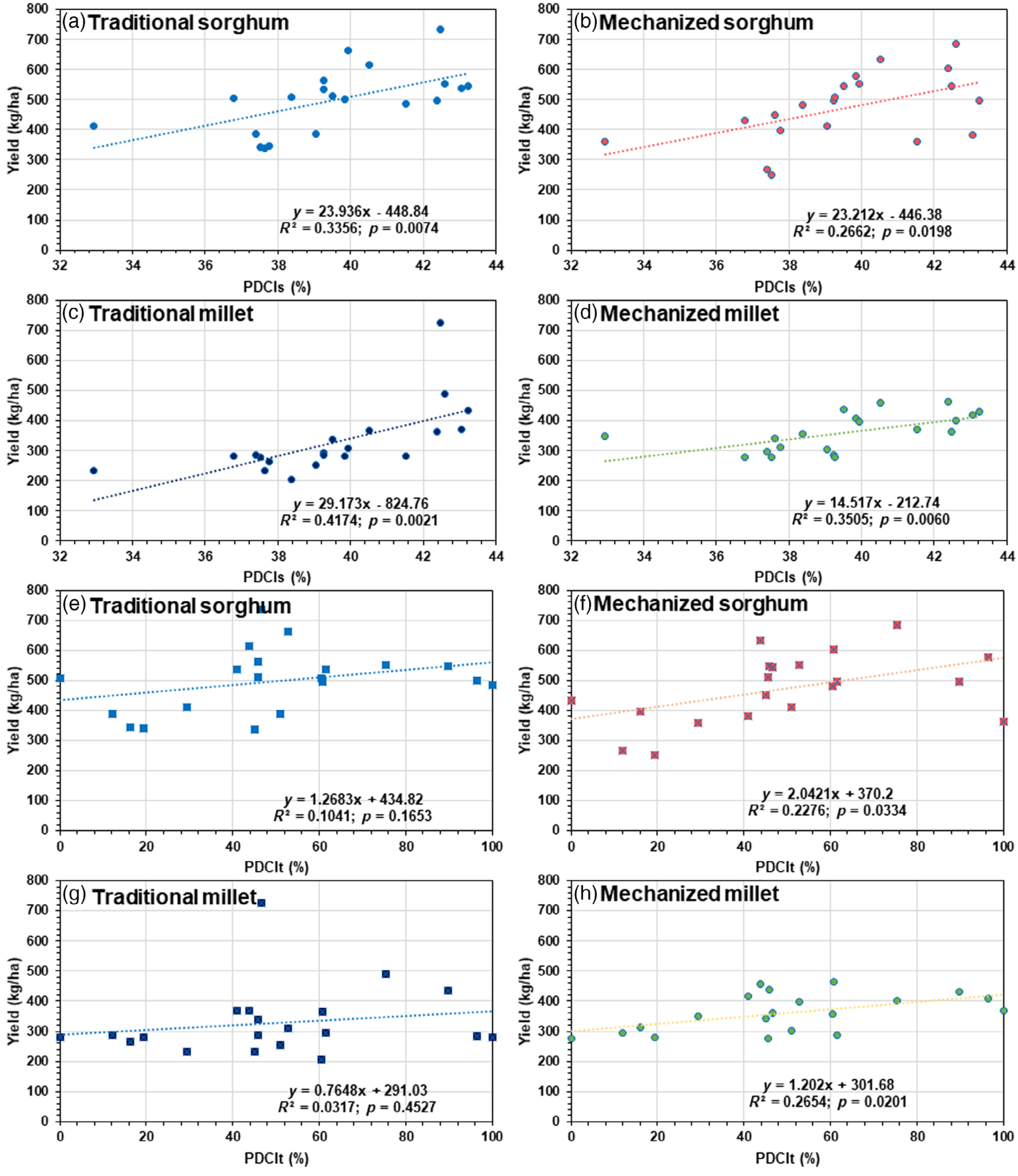

FIGURE 6 Crop yield for rainfed farming systems as a function of the space-dependent (a–d) and time-dependent (e–h) drought indices. The significance level is reported for the two-tailed correlation test.

resilience to drought. But, the scheme was relatively resilient in the second driest year (2004) when it reported nearly mean crop yield loss and second yield level.

The wettest years as defined by PDCIs (e.g., 2020 and 2019) were favourable for the mechanized farming system. No crop yield loss was noted, with an exception in 2019 for sorghum. Despite this

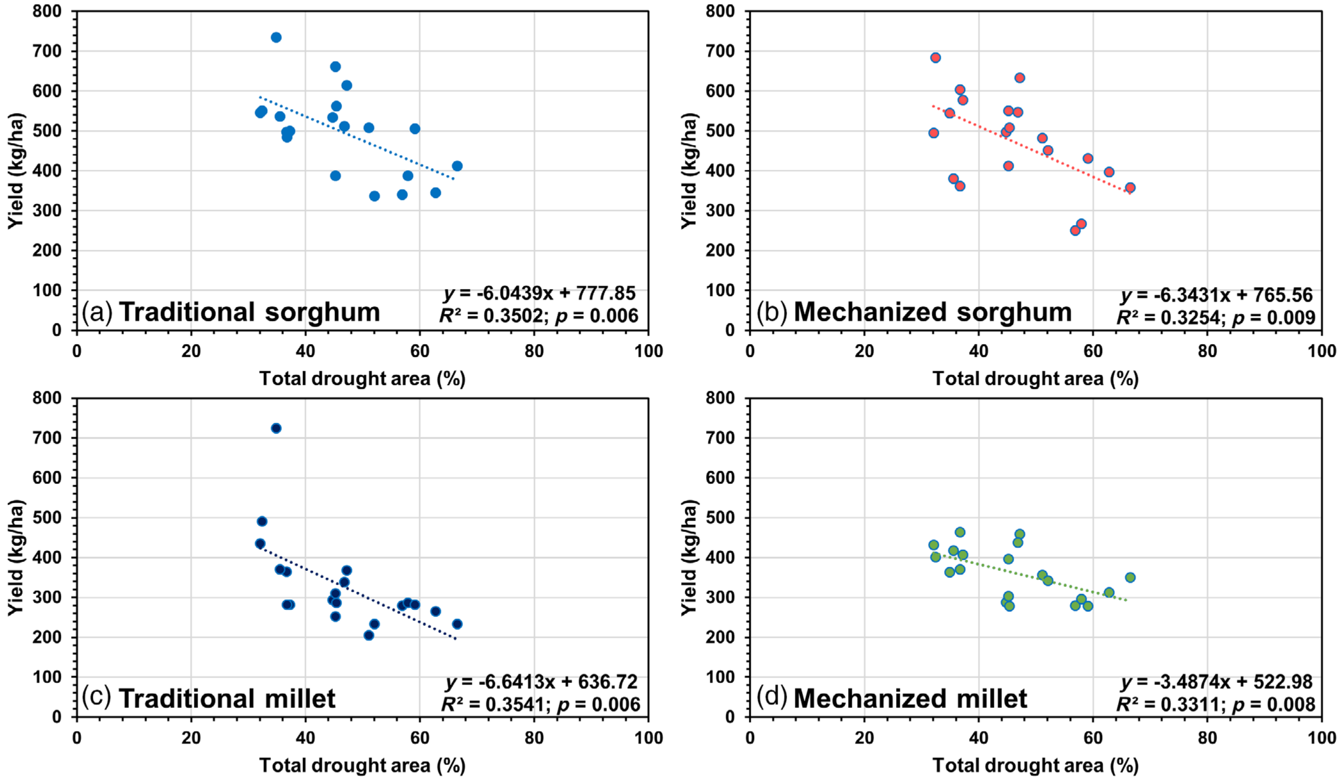

FIGURE 7 Relationship between yield and productivity-drought condition index-based percentage of total area under drought (shown in Figure 5) for rainfed farming systems. Only significant relationships are plotted. The significance level is reported for the two-tailed correlation test.

exception, the yield then was still slightly above average for the years with yield loss. Based on the PDCIt, the wettest conditions (e.g., 2007 and 2003) also benefited the crop yields in the rainfed sector with the exception of the mechanized farming in 2007. Moreover, the year 2020 was the third wettest for the rainfed system during the last two decades. The mechanized farming system was adaptive in this year. Even though the traditional sector encountered yield loss, the crop yield was still the highest reported during the loss years. Too wet conditions cause sorghum yield losses in the irrigated farming systems. Typical examples of this case were the wettest years 2020, 2003 and 2014 for the gravity irrigation system and 2020 and 2007 for the spate irrigation scheme. Nonetheless, the crop yield was still the highest recorded during the years with crop loss in the former system in 2020 and the latter system in 2007. The yield losses in these 2 years were the second smallest.

3.6 | Inter-comparison of yield levels and losses

There is a wide range of crop yield reported in years characterized by crop yield losses among the four farming systems (Figure 9). With regard to sorghum, the highest crop yield (2203 kg/ha) was achieved by the gravity-irrigated farming whereas the mechanized farming attained the lowest yield (251 kg/ha). On average, sorghum yield from the former system was 5 times that attained from the latter system. As regards the rainfed millet, the traditional sector attained a maximum yield of 435 kg/ha whereas the maximum yield achieved by the mechanized sector was 370 kg/ha. Statistical comparison using the *Z*-test of the average yields between any two farming systems that cultivate the same crop, that is, rainfed sorghum, rainfed millet or irrigated sorghum, did not show a significant difference in the means between the traditional and mechanized systems or the gravity and spate irrigation systems. Significance difference was found in the mean yield between the traditional or mechanized systems and the gravity or spate irrigation systems. No significant difference between the mean yield losses was found. Figure 9 shows, however, the following performance: the traditional sorghum or millet had lower yield loss compared to the mechanized crops. But, the average millet yield level is slightly higher (~8.7%) for the mechanized system than for the traditional one. The sorghum yield loss reported for the gravity irrigated system is lower than that remarked for the spate irrigated crop.

4 | DISCUSSION

4.1 | Fidelity of the developed index

For the first time, an assessment of the performance of the different Sahel farming systems is conducted. The classic VCI is modified herein first by using the productivity index (iNDVI) over the growing season

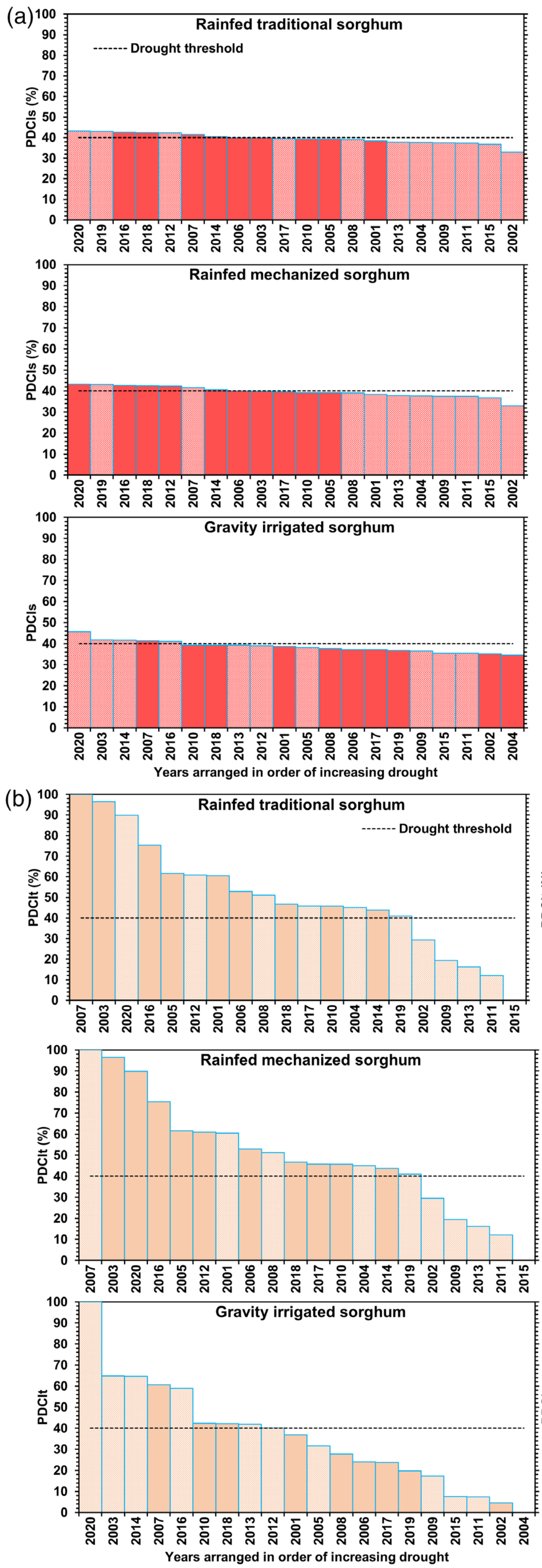

FIGURE 8 Ranking of productivity-drought condition index (PDCI) during the period 2001–2020 with years of yield losses indicated by patterned (lighter colour) bar: (a) using PDCIs and (b) using PDCIt.

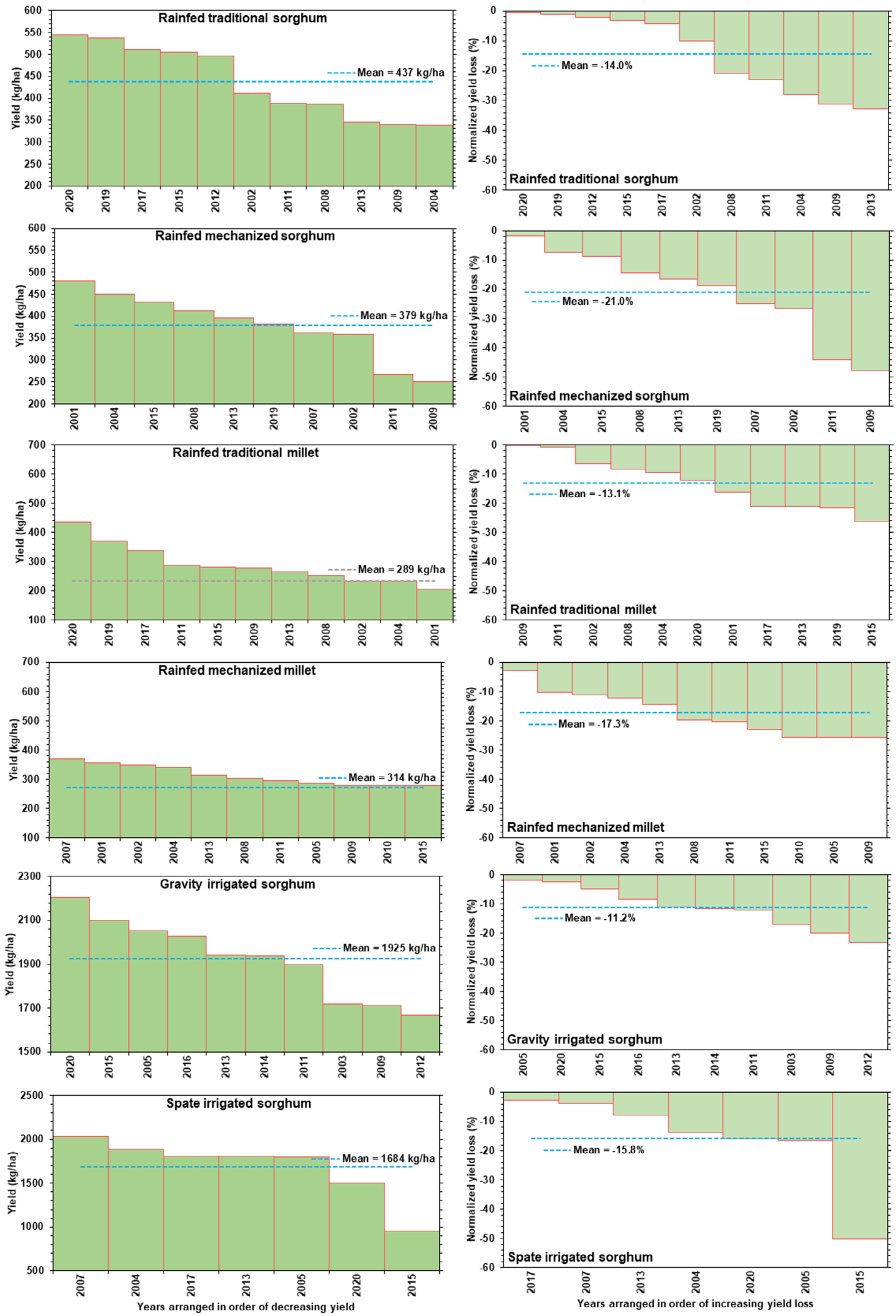

FIGURE 9 Ranking of crop yield (left) during the years reporting yield loss (right). Normalization of yield loss is relative to the yield trend obtained based on the regime shift analysis.

TABLE 2 Main drought and flood incidents reported in the literature for the Sahel during the period 2001–2020.

Year	References
Drought	
2002	Elagib and Elhag (2011); Elagib (2014, 2015)
2004	Elagib and Elhag (2011); Elagib (2014, 2015); Elagib et al. (2019)
2009	Elagib and Elhag (2011); Sulieman and Elagib (2012); Nicholson (2014); Elagib et al. (2019)
2010	Nicholson (2014)
2011	Cornforth (2012); Boyd et al. (2013); Nicholson (2014); Hermance et al. (2016); Elagib et al. (2019)
2012	Hermance et al. (2016); Elagib et al. (2019)
2015	Behnke et al. (2020); Eze et al. (2022)
Flood	
2003	Sulieman and Elagib (2012); Amarnath et al. (2016)
2007	Samimi et al. (2012); Amarnath et al. (2016); Elagib et al. (2019)
2013	Mahmood et al. (2017); Amarnath et al. (2018)
2014	IFRC (2014); Mahmood et al. (2017)
2019	Elagib, Al Zayed, et al. (2021)
2020	Elagib, Al Zayed, et al. (2021)

and secondly by devising a performance index (PDCI) in two versions, that is, space-dependent and time-dependent. It was possible to distinguish between the impacts of both scales on the productivity of the agricultural systems. The use of a single Sahel-wide maximum and minimum iNDVI to develop the space-dependent PDCI (PDCIs) proved to have several merits. It allowed mapping the sector-specific areas with similar severity of drought impacts across a given cropland in the region. On one hand, these maps provided information related to the effectiveness of the growing season rainfall for rainfed agriculture. For gravity-irrigated agriculture, on the other hand, these maps furnished a vital piece of information about the distribution of irrigation water across the irrigated schemes. Such maps, thus, convey information about the efficiency of the irrigation water supply system (Al Zayed et al., 2015). Moreover, the PDCIt invited us to apprehend the year-to-year variability in both the effectiveness of the seasonal rainfall and the efficiency of the irrigation and, in turn, the productivity of both sectors. The developed PDCI satisfied the mission of assessing the performance of both rainfed and irrigated agriculture alike.

In terms of quality and fidelity of the developed PDCI, it proved to capture the timing of the occurrence of hydrological extremes, whether droughts or floods, reported in the literature for the Sahel. Table 2 indicates the occurrence of seven drought events and six flood events in the Sahel region. The results described in Section 3 (Figures 8 and 9) together with Table 2 demonstrate the match of occurrence of these major drought and flood events, corresponding to years with crop yield losses and low yields. For example, Sulieman & Elagib, 2012 reported several poor conditions for sorghum production in 2009 in the densely mechanized region in Sahelian Sudan. They reported late and dry rainy seasons, a small number of rainy days with concentrated rainfall and a hottest year since 1941 with a 1.5–1.6°C rise in temperature above normal. These features thus led to a decline in sorghum yield to only 42% of the normal level (Sulieman & Elagib, 2012). The rainy season of the year 2011 was dismal as it resulted in severe drought-induced sharpening of the humanitarian and food insecurity impacts in West Africa (Cornforth, 2012; Boyd et al., 2013). Elagib, Khalifa, et al. (2021) marked the year 2011 as the third least productive within the period 1998–2017 in the area lying east of 10°E in the Sahel, following the years 2004 and 2000. Indeed, our results for the Sahel of Sudan detected yield losses and low yields in at least three farming systems in 2004 or 2011.

The iNDVI used to derive PDCI was originally obtained using 10-days composite of eMODIS NDVI product. Implementing the algorithm in real time for persistently cloudy areas can be challenging. To correct the quality of the data and obtain cloud- or atmospheric contamination-free observations, this product has an algorithm that smoothens the NDVI data after three composite periods using a time series approach. Interim graphics include masks based on cloud flags from the original data until the final corrected data are available. While the PDCI is used to indicate drought, it does so by using crop productivity as a proxy instead of an index based explicitly on water amount. On one hand, the PDCI index developed herein was able to capture the timing of drought and floods besides the years in which crop yield loss occurred. The PDCI is also workable in exploring the importance of the space dimension over the time dimension in explaining the effect of drought on crop yield levels among the farming systems (Figure 6). On the other hand, PDCI is not meant to work as a predictor of crop yield. This limitation is apparent from the R^2 in Figure 6 in spite of some significant values. The weak correlation is partly due to scale factor of the study. Here, we considered the region or the farming system as a whole as one unit regardless of the heterogeneity involved in such a large area. The region-wide or farming system-wide analysis does not consider the heterogeneity in crop types within a given farming system. The cropland within a farming system was rather considered to be cultivated solely by sorghum or millet. Additionally, the rainfed croplands, as classified by the land use dataset, do not take the difference between traditional and mechanized farming systems into account. Our study considered the same cropland in the analysis of both cases. There was no access for this study to detailed data on the cultivated areas. Moreover, the crop yield data used were assumed to relate to these four large-scale irrigated schemes only, thus neglecting the existence of other smaller irrigated schemes.

4.2 | Questioning the Sahel recovery from drought

Many examples have been gathered from around the African Sahel region dealing with the analysis of meteorological drought and recovery. However, grasping the complexity of interconnected recovery and agricultural outcomes remains indispensable. This necessity stems simply from the notion that this region is particularly characterized by highly variable climate, high vulnerability and food and water insecurity. If hydrological extremes (droughts and floods) are considered beyond the conceptual driver focus (Kchouk et al., 2022), the results of the present contribution lead to rejection of the general notion of Sahel recovery. Taking the impacts of these extremes as measures of water and food security, this study provides evidence of the occurrence of negative impacts and risks induced by droughts to staple food crops during the past two decades. Yield losses were reported in several years and for all farming systems—though with varying scales—as a result of drought events. Erratic rainfall usually determines the success or failure of the growing season and production level in the rainfed sector (Elagib, 2014, 2015; Elagib et al., 2019). While reasonably stable productivity is a prima facie benefit from irrigation supplemental to rainfall (CFSAM, 2011; Elagib, 2014, 2015), it is not in accordance with expectations in the present Sahel example.

4.3 | Differential effects of droughts and floods and policy implications

Droughts and floods trigger impacts that have the potential to lead to a sequence of interacting entitlement failures related to food security (Devereux, 2007). According to Devereux (2007), these entitlements include disruption of production, labour or employment, trade or commodity markets and transfer of food aid or cash transfers, ultimately turning into a livelihood crisis. While both, droughts and floods, may have severe effects upon agricultural yield, they are very different in terms of their temporal and spatial character. Drought typically affect large regions. The dominating effect of droughts on agricultural yield is a function of the integral over time and water deficit. Floods however are usually limited to smaller areas due to the topographic accumulation of runoff. In contrast to drought risk, this study illustrates some differences in the flood impacts on agricultural productivity. While floods have the potential to pose risk to crop yield, the yield loss is either nil for the mechanized rainfed sector or is least for the traditional rainfed sector. Floods have mixed impacts (nil or quite low) on the gravity irrigation sector. Yield losses, though small, occurring in this sector during extremely wet years are attributable to over-irrigation resulting from overlooking or wasting the supplemental rainwater supply (Al Zayed et al., 2015; Al Zayed & Elagib, 2017). Ayanlade et al. (2022) argue that more than irrigation technology, farmers in Sub-Saharan Africa need to adopt adaptation strategies that improve water efficiency. Nevertheless, the high yield reported in this sector during these yield loss years may indicate some positive feedback. Too wet conditions, for example, may bring about more water supply to areas that usually suffer shortage of water in general or irrigation water in particular (Al Zayed et al., 2015; Al Zayed & Elagib, 2017; Khalifa et al., 2020). Conversely, the spate irrigation sector is severely impacted by floods in terms of yield levels and losses. In any case, water policymakers should observe water saving and efficient utilization of water to improve agricurural productivity (Al Zayed & Elagib, 2017; Elagib, Al Zayed, et al., 2021).

Unlike flood impacts, drought impacts on agricultural production in the Sahel tend to experience high research, governmental and public recognition and reporting. The more recent flood years should, however, guide similar attention to the risk posed by flood episodes under a changing climate in the Sahel (Elagib, Al Zayed, et al., 2021). Findings by Elagib (2010) for eastern Sudan showed that the annual rainfall is highly dependent on heavy rainfalls (daily >30 mm) and is independent of light and medium rainfall events. This result was interpreted as indicating that heavy rainfalls are more likely to diminish in drought years and increase in wet years (Elagib, 2010). Sulieman & Elagib, 2012 further found a year with such heavy falls was associated with less agricultural land compared to years with better rain distribution over the season. Ly et al. (2013) recommend redesigning the infrastructure and production systems to account for risks of losses induced by both floods and droughts. Recent studies recommended harvesting the floodwater for irrigation purposes in the Sahel instead of being seen as a damaging resource (Atanga & Tankpa, 2021; Elagib, Al Zayed, et al., 2021). Directing and guiding future studies and predictive assessment of flood-related impacts on food security in Africa necessitate the collection of relevant data and information (Reed et al., 2022).

Findings drawn by this study indicated higher sorghum yields attainable in the traditional system than in the mechanized farming system. Furthermore, sorghum and millet yield losses in the mechanized system were larger than in the former farming sector. These findings are somewhat surprising, as one would expect the opposite to be true. It is argued that more attention is paid to good farming practices by farmers in the traditional subsector than by the investors in the mechanized subsector (CFSAM, 2011). This perception is likely due to the fact that traditional farming systems belongs to smallholders who spend more work hours on small fields compared to the mechanized systems, which belong to large farms with little work hours per cultivated area. Moreover, the farmers' decisions in mechanized sorghum farming systems are challenged by many variables, such as monocropping, soil fertility, weed invasion, crop cultivars, and so forth (Bussmann et al., 2016; Shepherd, 1983). As for millet, this crop has better suitability to the ecological conditions of the area (e.g., sandy soil and inadequate moisture conditions) and has sour taste to birds (Abu Sin, 1986; Blum & Sullivan, 1986; Gregory, 1982). Thus, millet yield under mechanization is generally higher than that under traditional conditions though yield losses is lower for the traditional case under hydrological extremes (Figure 9).

As Ayanlade et al. (2022) argued, technology transfer requires 'knowledge and skills and the development of the capacity to use and adapt the technology' more than just equipment and machinery. Implementation of technological development without prior assessment may lead ultimately to long-term and permanent losses in spite of the initial gains (Glantz, 1977). There is a notion according to Bussmann et al. (2016) that 'not only irrigated but also rainfed agriculture needs to receive increasing recognition by the Sudanese government'. More intensive farming practices are attended to in the irrigated sector than in the rainfed sector (CFSAM, 2011). These notions are corroborated by the wide gap observed in this study in crop yield between the rainfed and irrigation sectors.

5 | CONCLUSIONS

With the aim being to investigate the state of the recent Sahel recovery from drought, the present study made progress regarding the analysis of the performance of the farming systems in the African Sahel region during the past 20 years. Taking the Sahel zone of Sudan as a principal case of an agriculture-based economy, remotely sensed vegetation greening was used as a proxy for productivity to express productivity-drought conditions scaled in both space and time. The newly devised PDCI was found useful in capturing the performance of the various Sahel farming systems under both hydrological extremes, that is, droughts and floods.

A number of concluding results can be succinctly summarized. The region was hit by a number of dismal drought events despite being interrupted by wet (or flood) years. The percentage of the areal extent of drought across the irrigated farming system is generally higher than that across the rainfed counterpart. In terms of agricultural farming outcomes, the situation in the region does not seem to have reverted to conditions that could be prescribed as a Sahel recovery. In comparison to flooding, drought remains a blight on the Sahel's agricultural prospects. Flood risk to crop yield is usually lower and may even enhance yield in some events. Drought severity as expressed by either a space or a time dimension explains the crop yield of the rainfed systems at a significant level unlike the yields of the irrigated systems. There is, however, more relevance of space than time dimension of drought to the rainfed yield. Crop yield under rainfed conditions vary inversely with severity and areal extent of drought. Unlike the rainfed mechanized sector, both the rainfed traditional and irrigated systems are not resilient to extreme wet conditions (e.g. year 2020) in terms of reduced yield. During years of sorghum yield losses, the rainfed traditional farming systems performed better than the rainfed mechanized systems. On average, rainfed millet in the mechanized sector performs slightly better (poorer) than in the traditional sector in terms of yield level (yield loss). In terms of both the yield level and yield loss, sorghum under gravity irrigation performs better on average than under spate irrigated system.

Since the findings of this study show that losses due to droughts are usually larger than those caused by floods, drought-related measures that lessen losses due to drought in the agricultural sector should be prioritized. However, future studies should also put flood impacts on different farming systems on the research agenda of the region. This research policy will help recognize the combined important implications of both hydrological extremes for food security in the region. Against the background of recent dismal occurrence of hydrological extremes, more attention should be attracted to addressing the research gap in how the Sahel farming systems should adapt and/or mitigate the consequent risks. While we provided evidence of suitability of the present approach to assessing the performance of the farming systems on the large scale of the entire Sahel region, the same approach is also applicable on the finer scale (e.g., state/scheme). Towards improving the water-use efficiency and crop productivity, the diagnostic information laid in this work can be regarded as a promising input for management decisions in the various farming systems of the region in response to climate variability.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Land use data (The global HIstoric Land Dynamics Assessment, HILDA+) from which croplands were obtained are retrievable from https://doi.org/10.1594/PANGAEA.921846. Crop statistics can be requested from the Ministry of Agriculture and Natural Resources of Sudan. The Moderate Resolution Imaging Spectroradiometer (eMODIS NDVI collection 6) from which the dekadal data on Normalized Difference Vegetation Index can be retrieved from https://earlywarning.usgs.gov/fews/datadownloads/East%20Africa/eMODIS%20NDVI%20C6 (last accessed 16 January 2022). Access to the eMODIS NDVI from this site has been suspended until further notice (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-vegetation-monitoring-eros-moderate-resolution-imaging). However, access can alternatively be given to eMODIS NDVI C6 for East Africa using the link: https://edcintl.cr.usgs.gov/downloads/sciweb1/shared/fews/web/africa/east/dekadal/emodis/ndvi_c6/

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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