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Trends and impacts of climate change on crop production in Burkina Faso

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ABSTRACT

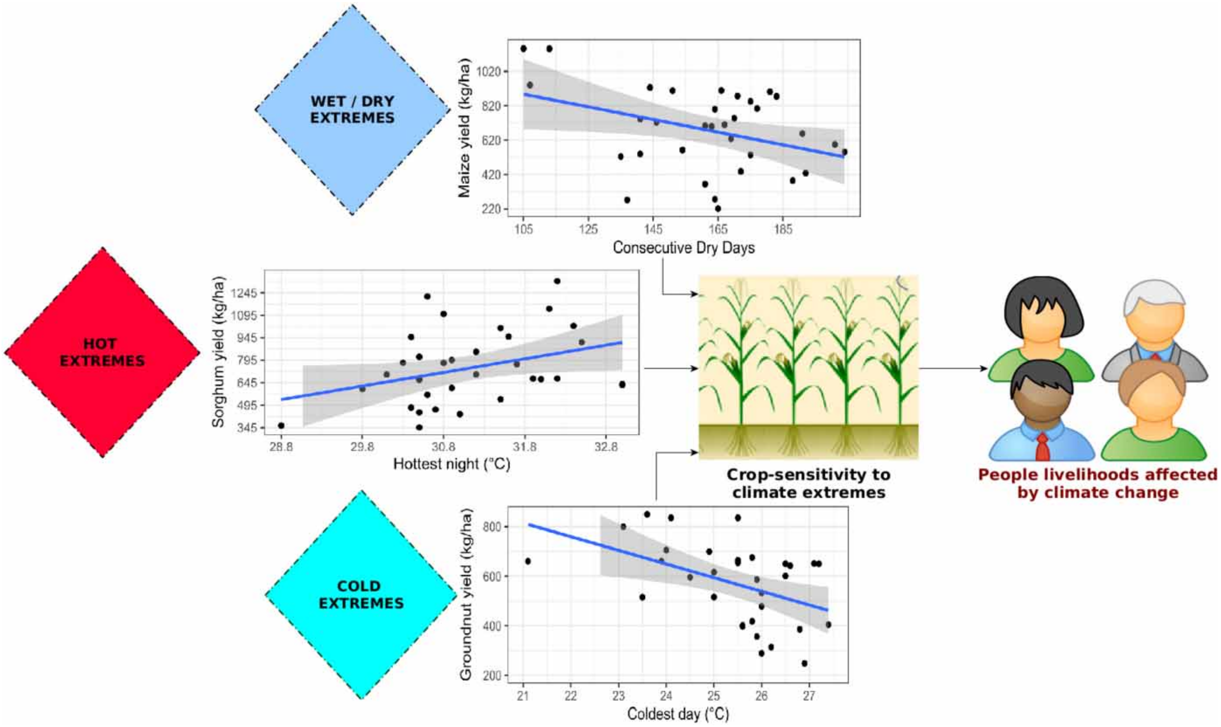
Understanding past climate trends and their impacts in the Sahel region is fundamental for climate change (CC) adaptation and mitigation. This study analyses climate trends from 1961 to 2020 in three climatic zones in Burkina Faso and the impacts of CC on five major crops production. Long time series of daily rainfall and temperature data from National Meteorology Agency for the period 1961 to 2020 has been compiled. Crop production data (1984–2020) were retrieved from the agriculture department. Climate temporal variations in each climatic zone were analyzed using extreme climate indices and principal component analysis. Linear regression was used to assess climate impacts on crop production. The results showed a high rainfall variability and changes in temperature extremes in the three zones. The climate window, 1991–2020, was hotter than 1961–1990, while the last decade (2011–2020) was the wettest. Most climate indices (67%) showed significant correlations with crop yields. Dry spells, cool days, cold nights, average daily wet days and rainfall intensity showed positive and negative effects on maize, cowpea, millet and sorghum yields. This study highlights the importance of climate-smart policy promoting drought-resistant and short-duration varieties in addressing the adverse effects of CC on crop production.

Key words: climate change, climate extreme, food security, West African Sahel

HIGHLIGHTS

- The warm tails of the daily temperature distributions are changing faster than the cold tails witnessing a warming climate in Burkina Faso.
- Recent decade was wetter across the Sahelian and Sudano-Sahelian zones, supporting rain resumption and the Sahel greening hypothesis.
- The major crops were differently affected by climate extremes and were more sensitive to these extremes than the average climate conditions.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Global climate change (CC) constitutes an important challenge worldwide with severe impacts on sustainable development. Over the 20th century, climate conditions have experienced significant changes in many regions worldwide driven by a continuous increase in global greenhouse gas emissions. This has caused a long-term warming trend since pre-industrial times, estimated at 0.2 °C per decade due to past and ongoing emissions (IPCC 2022).

This century revealed an increasing trend of the global mean surface temperature (Wedajo *et al.* 2021; Worku *et al.* 2022) and precipitations (Nouaceur & Murarescu 2020; Wedajo *et al.* 2021). At the regional or local scale, both increases and decreases in the spatiotemporal trends of precipitations are observed (Berg & Sheffield 2018; Atiah *et al.* 2021). Several studies reported increased and decreased trends of climate extremes, such as hot days/heat index and cold/frost days, were experienced, respectively, for nearly all land areas during this century (Sillmann *et al.* 2013).

Mean temperature was projected to rise from 3 to 4 °C leading to a 15–35% loss in crop yields in Africa and West Asia this century (Chadalavada *et al.* 2021). Similarly, about 25–35% of yield loss is expected in the Middle East with a temperature rise of 3–4 °C (Chadalavada *et al.* 2021).

West Africa is a CC hotspot region characterised by high climate variability, extreme climatic events, severe exposure and low adaptive capacity (Heubes *et al.* 2013). CC in this region negatively impacts agricultural production (Heubes *et al.* 2013; Nelson *et al.* 2018) and strongly affects the well-being of poor households relying on natural resources (Jones & Thornton 2009) and cropping for their survival. Altered climate conditions in West Africa are reported to cause yield declines of 10–20% for millet and 5–15% for sorghum (El Bilali 2021). The decline in crop yield implies income reduction for farmers and the country's economy (El Bilali 2021) and less resilience to global changes. Inappropriate or poor adoption of mixed cropping in the region contributes to low resilience (Ifejika Speranza 2010; Devkota *et al.* 2022).

Like most West Sahelian countries, Burkina Faso strongly depends on agriculture and animal breeding. Farmers in Burkina Faso are more vulnerable to CC because usually, they have very few alternatives facing climate risk. Cropping systems are predominantly subsistence-oriented, with mainly small holdings characterised by small farm size and highly variable herd size and composition. Cereal crops such as sorghum (*Sorghum bicolor*), millet (*Panicum* sp.) and maize (*Zea mays L.*) constitute the main pillars of Burkina Faso's food security and across West Africa (Waongo *et al.* 2015). Besides these cereal crops are groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*), which are double staple and cash crops for vulnerable smallholder farmers in Burkina Faso.

In recent decades, there has been a growing literature on CC and variability in the West African Sahel (Pirret & Daron 2019). Yet, these studies were more based on farmers' perceptions and impact simulations from models. Unavailability of long-term data is a common challenge for most West African countries. In Burkina Faso, the longest available time series data on the targeted study zones was about 37 years. Therefore, most studies relied on satellite data or resorted to surveys in assessing CC impact on crop production. Accordingly, updated data on crop's sensitivity to CC, namely to climate extremes, are lacking in Burkina Faso. Furthermore, most of the studies focused only on the impact of raw climate variables (mean temperature and rainfall) on crop production. This may hide some effects posed by climate extremes. From this perspective, the current study used climate cold, hot and wet indices as predictors in the analysis of climate implications on crop production across climatic zones of Burkina Faso. Specifically, this study sought to:

(i) analyse extreme climate indices across different climatic zones of Burkina Faso;
(ii) analyse the influence of extreme climate indices on the yield of five major crops in Burkina Faso. We hypothesise an increasing CC impacts on crop yield with the climate gradient.

Findings from this study may contribute to a better understanding of the influence of CC and variability on crop yield in the West African Sahel, which is of great relevance for farmers and policymakers to address food security.

2. MATERIALS AND METHODS

2.1. Study area

The study was carried out in Burkina Faso, a Sahelian West African country located between the latitudes 09°02′–15°05′ N and the longitudes 02°02′ E–05°03′ W. Burkina Faso is in the Sahelian transitional and the Sudanian regional centre of endemism (White 1983), covering the major bioclimatic gradient in West Africa (Heubes *et al.* 2013). The study area includes three provinces distributed along the three climatic zones of Burkina Faso. The study sites were Seno (13°32′13.2″ N–14°28′12″ N and 0°37′30″ W–0°32′60″ E) in the Sahelian zone, Kourweogo (12°17′24″ N–12°54′18″ N and 2°4′55.2″–1°35′42″ W) in the Sudano-Sahelian zone and Ioba (10°42′7.2″ N–12°54′18″ N and 3°26′56.4″–2°36′39.6″ W) in the Sudanian zone (Figure 1). The climate is tropical sub-arid to sub-humid with a unimodal rainfall regime. The sites are aligned along a climatic gradient characterised by a North to South increase in mean annual rainfall (300–1,200 mm year^{-1}) and a decrease in mean annual temperature (35–20 °C) (Table 1). Livestock and crop farming represent the two main socio-economic activities in the study sites. Livestock rearing is more practiced in the Sahel than cropping. Local populations practice more crop farming than livestock breeding in the Sudanian zone where rainfall is more favourable. Across the three climatic zones, cereal crop production is predominantly subsistence-oriented (Waongo *et al.* 2015).

2.2. Data collection

2.2.1. Climate data

Long time series of climate records spanning the last 60 years (1961–2020) were obtained from the National Agency of Meteorology of Burkina Faso. The daily climate datasets (rainfall, maximum and minimum temperature) were from three weather stations, each located in one of the three climatic zones of Burkina Faso, Dori in the Sahelian zone, Ouagadougou in the Sudano-Sahelian zone and Gaoua in the Sudanian zone.

2.2.2. Crop production data

This study considered five major crops: maize, millet, sorghum, cowpea and groundnut. Maize, millet and sorghum represent staple crops and greatly contribute to food security in the West African region (Waongo *et al.* 2015). Cowpea and groundnut are cash crops and sources of income for smallholder farmers. In each climatic zone, we collected data on annual yields (kg/ha) of the five crops from 1984 to 2020 from the Ministry of Agriculture. The crops data were obtained from three provinces: Seno in the Sahelian zone, Kourweogo in the Sudano-Sahelian zone and Ioba in the Sahelian zone.

2.3. Data analysis

Data were quality controlled before subsequent analysis. Missing data were not filled but substituted with the value −99.9 in the input text files as required by ClimPACT2 (Alexander & Herold 2016). Homogeneity of data was tested with RhtestsV4 package and the Quality Control (QC) option in ClimPACT2 to remove outliers like minimum temperature greater than

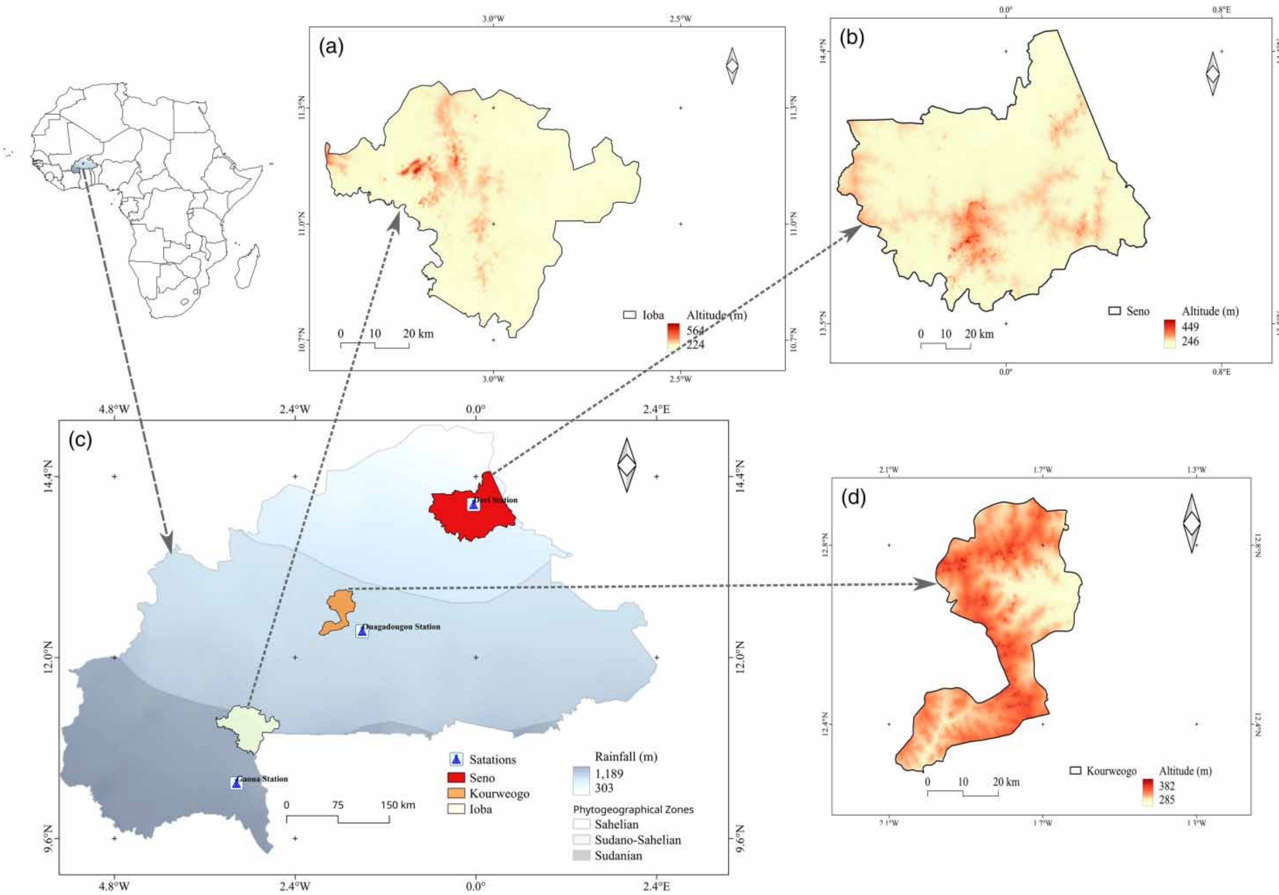


Figure 1 | Location of the study provinces across climatic zones of Burkina Faso. (a) Province of Seno; (b) Province of Kourweogo; (c) Province of Ioba; (d) Map of Africa.

Table 1 | Climate characteristics of the study sites in Burkina Faso

Sites	Climatic zones	MAP (mm)	MAT (°C)	Rain days (d)	RSL (d)	STR (°C)
Dori	Sahelian	300–600	25–35	<45	110	11
Niou	Sudano-Sahelian	600–900	20–30	50–70	150	8
Dano	Sudanian	900–1,200	20–25	85–100	180–200	5

Source: PANA Burkina (2007).

MAP, mean annual precipitation; MAT, mean annual temperature; RSL, rainy season length; STR, seasonal temperature range.

maximum temperatures and negative temperature records (Alexander & Herold 2016). The homogenised data was subsequently used in the multiple regression analysis between climate extremes and crop production.

To assess climate trends in the three climatic zones, 23 climate extreme indices known as best climate descriptors were selected among the 64 indices commonly used for climate trends analysis (Alexander & Herold 2016). The first 10 out of the 23 selected indices (Table 2) have important implications in the sectors of agriculture and food security, water resources and hydrology (Alexander & Herold 2016). These indices were computed using the R package ClimPACT2 GUI (Alexander & Herold 2016). We also considered other indices such as warm spell, cold spell, dry spell, wet spell, rainfall anomaly and intensity which better describe climate conditions in Burkina Faso where high temperature and irregular rainfall strongly determine water flow and availability for cropping. Moreover, water availability for plant use was highly influenced by the evapotranspiration, which is also influenced by temperature. Climate indices trends were based on Sen's slope (using the

Table 2 | Characteristics of climate indices analysed in the study

Indices	Definition	Plain language description	Importance
TXx (°C)	Warmest daily maximum temperature (TX)	Hottest day	AFS
TNn (°C)	Coldest daily minimum temperature (TN)	Coldest night	AFS
TR (days)	Annual count of days when TN > 20 °C	Days when the minimum temperature exceeds 20 °C	H, AFS
WSDI (days)	Annual number of days contributing to events where six or more consecutive days experience TX > 90th percentile	Number of days contributing to a warm period (where the period has to be at least 6 days long)	H, AFS, WRH
CSDI (days)	Annual number of days contributing to events where six or more consecutive days experience TN <10th percentile	Number of days contributing to a cold period (where the period has to be at least 6 days long)	H, AFS
CDD (days)	Maximum number of consecutive dry days (PR < 1.0 mm)	Longest dry spell	H, AFS
SPEI 12	Measure of 'drought' using the Standardised Precipitation Evapotranspiration Index on time scales of 12 months	A drought measure specified using precipitation and evaporation	H, AFS, WRH
SPI 12	Measure of 'drought' using the Standardised Precipitation Index on time scales of 12 months	A drought measure specified as a precipitation deficit	H, AFS, WRH
PRCPTOT (mm)	Sum of daily PR >= 1.0 mm	Total wet-day rainfall	AFS, WRH
R20mm (days)	Number of days when PR >= 20 mm	Days when rainfall is at least 20 mm	AFS, WRH
SDII (mm/d)	Annual total PR divided by the number of wet days (when total PR >= 1.0 mm)	Average daily wet-day rainfall intensity	NE
R10mm (days)	Number of days when PR >= 10 mm	Days when rainfall is at least 10 mm	NE
TX10p (%)	Percentage of days when TX <10th percentile	Fraction of days with cool day time temperatures	NE
TX90p (%)	Percentage of days when TX > 90th percentile	Fraction of days with hot day time temperatures	NE
TN10p (%)	Percentage of days when TN <10th percentile	Fraction of days with cold night time temperatures	NE
TN90p (%)	Percentage of days when TN >90th percentile	Fraction of days with warm night time temperatures	NE
TMm (°C)	Mean daily mean temperature	Average daily temperature	NE
TXm (°C)	Mean daily maximum temperature	Average daily maximum temperature	NE
TNm (°C)	Mean daily minimum temperature	Average daily minimum temperature	NE
TNx (°C)	Warmest daily minimum temperature (TN)	Hottest night	NE
TXn (°C)	Coldest daily maximum temperature (TX)	Coldest day	NE
DTR (°C)	Mean difference between TX and TN	Average range of TX and TN	NE
CWD (days)	Maximum annual number of consecutive wet days (when PR >= 1.0 mm)	The longest wet spell	NE

H, health; AFS, agriculture and food security; WRH, water resources and hydrology; NE, non-evaluated against specific sector.

zyp package in R) (Alexander & Herold 2016). Sen's slope reflects the median slope of all ordered pairs of points in a dataset and is more appropriate for calculating trends in extreme values. Sen's slope analysis is a non-parametric method (Sen 1999).

To determine the importance of each selected index and the most affected decades in terms of climate deterioration within each climatic zone, we first computed the means values of climate indices over six decades (1961–1970, 1971–1980, 1981–1990, 1991–2000, 2001–2010 and 2011–2020). Afterwards, climate indices were subjected to principal component analysis (PCA) using the R package 'FactomineR' (Lê *et al.* 2008). For this purpose, time series of chosen indices were split and analysed according to the six defined decades within each climatic zone.

Pearson correlation test and multiple linear regression analyses were performed to assess the influence of extreme climatic conditions on the yields of the five crops. Mean temperature, total precipitation, precipitation intensity and climate extreme indicators were used as predictors. Climate data from 1984 to 2020 fit the time series length of crop yield data.

We assumed non-climatic factors (physiographic, edaphic, biotic and socio-economic) affecting crop production to be constant to investigate how extreme climatic indices alone could influence yield patterns in the study area.

3. RESULTS AND DISCUSSION

3.1. Trends of extreme climate indices (1961–2020)

3.1.1. Trends in rainfall climate extremes

The drought index indicating water availability in a year for crop use significantly increases in the Sahelian zone (for the Standardised Precipitation Evapotranspiration Index (SPEI)) and the Sudanian zone (Standardised Precipitation Evapotranspiration Index (SPEI) and Standardised Precipitation Index (SPI)). The trend was insignificant in the Sudano-Sahelian zone (Figure 2 and Supplementary Appendix 1). Moreover, no clear trend was observed in the annual rainfall pattern over the long period of 1961–2020 (Figure 2). However, a significantly increasing trend of rain was observed between 1984 and 2020 in all the zones except the Sudanian zone ($p < 0.05$) (Supplementary Appendix 2). This implies a re-wetting trend in the Sahelian and Sudano-Sahelian zones of Burkina Faso over the last three decades corroborating rain resumption and the Sahel greening hypothesis since the 1980s (Bichet & Diedhiou 2018; Biasutti 2019). Contrary to these findings, De Longueville *et al.* (2016) pointed out the decrease in total rainfall as the most significant change in all climatic zones of Burkina Faso until 2013. This difference could be due to the differences in the range of time series climate data studied by both studies.

3.1.2. Trends in temperature climate extremes

Generally, the climate extremes indices revealed a warming trend throughout the three climatic zones from 1961 to 2020 (Supplementary Appendix 3). Cold extremes indices (Cold spell duration indicator (CSDI), Amount of cool days (TX10p), Amount of cold night (TN10p)) (Supplementary Appendix 4) showed a decreasing trend. In contrast, hot extremes (Hottest day (TXx), Hottest night (TNx), Warm spell duration indicator (WSDI), Amount of hot days (TX90p), Amount of warm nights (TN90p)) revealed an increasing trend across all the studied zones ($p < 0.05$). The findings are within the range reported by Panda *et al.* (2014) for India for the period 1971–2005. It could imply that the patterns of extreme temperature indices after the pre-industrial age in the tropics are similar. Furthermore, the coldest night (TNn) and coldest day (TXn) generally showed an increasing trend in all zones, indicating a reduction in the intensity of cold nights and days in the country. Our findings suggest an overall warming trend in Burkina Faso, as reported by several studies conducted in West Africa (New *et al.* 2006; Barry *et al.* 2018). According to Barry *et al.* (2018), warm days and nights have become more frequent in Burkina Faso during 1960–2010. A warming trend of both days and nights between 1961 and 2000 was also observed within West Africa (New *et al.* 2006).

These warming trends have several implications on the agricultural sector. Temperature increase within an optimal range induces an increase in yield whereas below or beyond the optimal range results in reduced yield (Parthasarathi *et al.* 2022). This is because crops speed through their development with a temperature beyond the optimal temperature range, producing less grain (Cline 2008). Excessive temperature stresses lead to various physiological and biochemical changes in crops during their phenological development (Parthasarathi *et al.* 2022; Bita & Gerats 2013). High temperatures decrease seed germination percentage, plant emergence, results in poor seedlings vigour, abnormal seedlings, and further decrease radicle and plumule growth (Parthasarathi *et al.* 2022). Furthermore, excessive temperatures disturb the water cycle and interfere with crops ability to access and use moisture (Cline 2008). Both evaporation from soil and plants and transpiration are accelerated by a temperature rise (Cline 2008).

The number of normal nights is continuously converted into both extremes of hot or cold nights, implying a lack of a clear pattern in the trend of night extremes in the Sudanian zone (night cooling or warming) as observed (night warming) in the Sudano-Sahelian and the Sahelian zone ($p < 0.05$). This trend was consistent with the diurnal temperature range (DTR), which showed no significant trend in the Sudanian climatic zone but significantly increased in the Sahelian and Sudano-Sahelian zones. Our findings disagree with previous studies on climate extremes within West African regions (New *et al.* 2006; Barry *et al.* 2018) and highlight the accuracy of climate trend-related studies at the local scales. These results suggest more changes in climate conditions across the Sahelian and Sudano-Sahelian zones of Burkina Faso, contrary to the Sudanian zone.

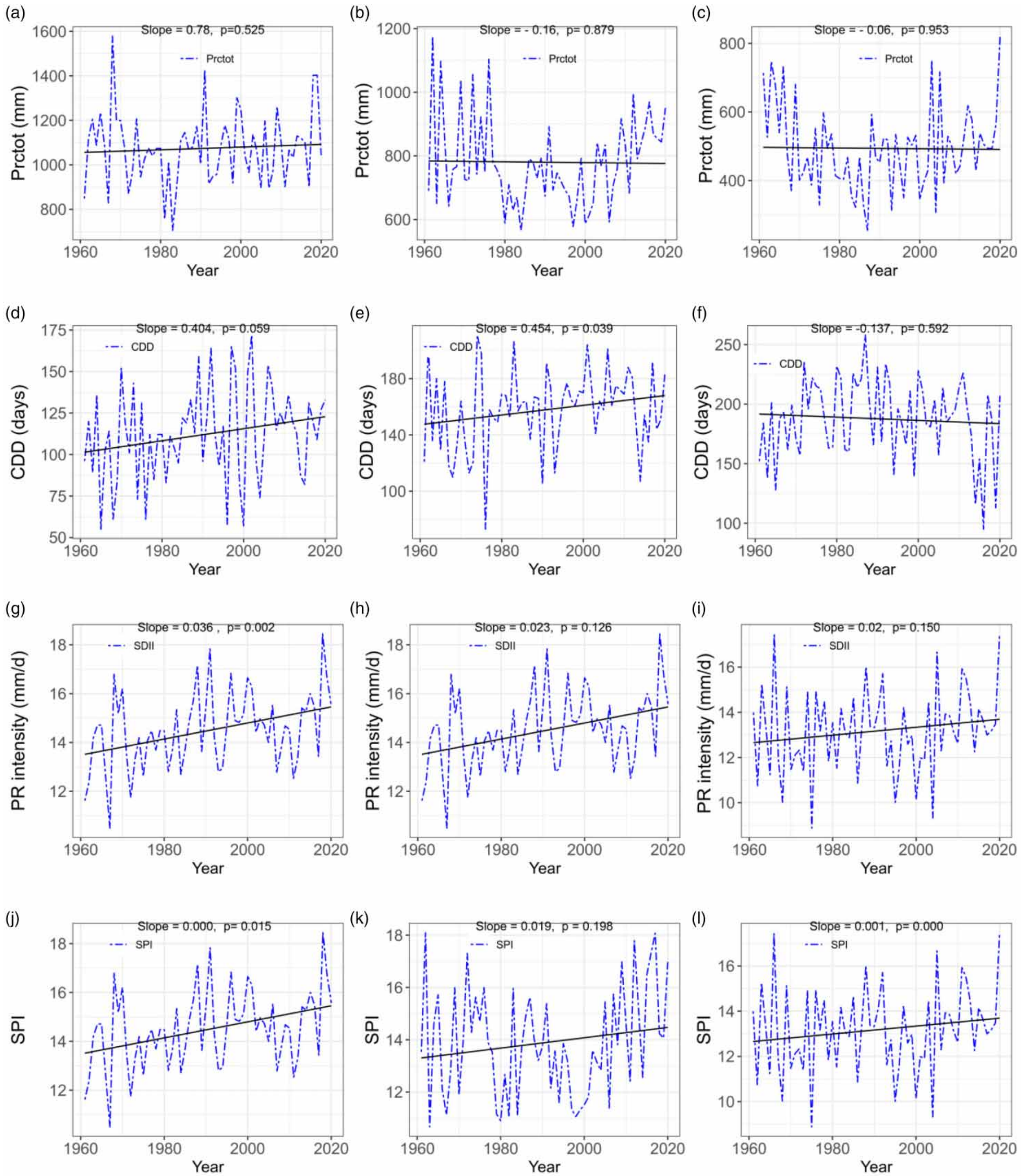


Figure 2 | Trend in the annual rainfall and wet indices in Sudanian (a,d,g,j), Sudano-Sahelian (b,e,h,k) and Sahelian (c,f,i,l) zones of Burkina Faso over the period 1961–2020.

The Sahelian and Sudano-Sahelian zones experienced longer cold spells (CSDI) between 1961 and 2020, while shorter cold spells characterised the Sudanian zone. Results in the Sudanian zone are consistent with New *et al.* (2006), who reported a decrease of a cold spell in West Africa. The Sudano-Sahelian zone, which constitutes the transition between the Sahelian zone and the Sudanian zone experienced a persistence in warm period as revealed by the WSDI within the study period (1961–2020). This result corroborates previous studies (New *et al.* 2006) supporting an average increase of warm spells by 2.4 days per decade in the West African region.

The comparison between cold and hot climate extremes revealed that hot extremes evolve faster than cold extremes. This finding suggests that the warm tails of the daily temperature distributions are changing faster than the cold tails.

3.2. Decadal variations in climate conditions

The PCA revealed different patterns of decadal climate conditions within the study area over the last six decades for both rainfall and temperature, with the Sahelian and the Sudano-Sahelian being the most vulnerable to CC compared to the Sudanian zone.

3.2.1. Rainfall climate extremes

Generally, rainfall and water availability within the three zones studied revealed a high variability over six decades (2011–2020, 2001–2010, 1991–2000, 1981–1990, 1971–1980 and 1961–1970) of the 60 years (1961–2020). However, the last decade (2011–2020) was found to be the wettest of the period in all three climatic zones (Figure 3 and Supplementary Appendices 5 and 6), ascertaining the resumption of rains observed in the recent years over the Sahelian region of West Africa (Nouaceur & Murarescu 2020). The decade 1981–1990 was the driest in all the zones with generally a low annual rainfall amount and longer dry spells in general. These driest conditions can be explained by the consecutive three-year drought (1982–1984) in the Sahelian countries within the same period. This drought was more acute than that of 1972–1973. Furthermore, the period 1981–1990 falls within the drought extreme period (1977–1990) recorded in Burkina Faso according to Nouaceur & Murarescu (2020) (Figure 3 and Supplementary Appendices 5 and 6).

3.2.2. Temperature climate extremes

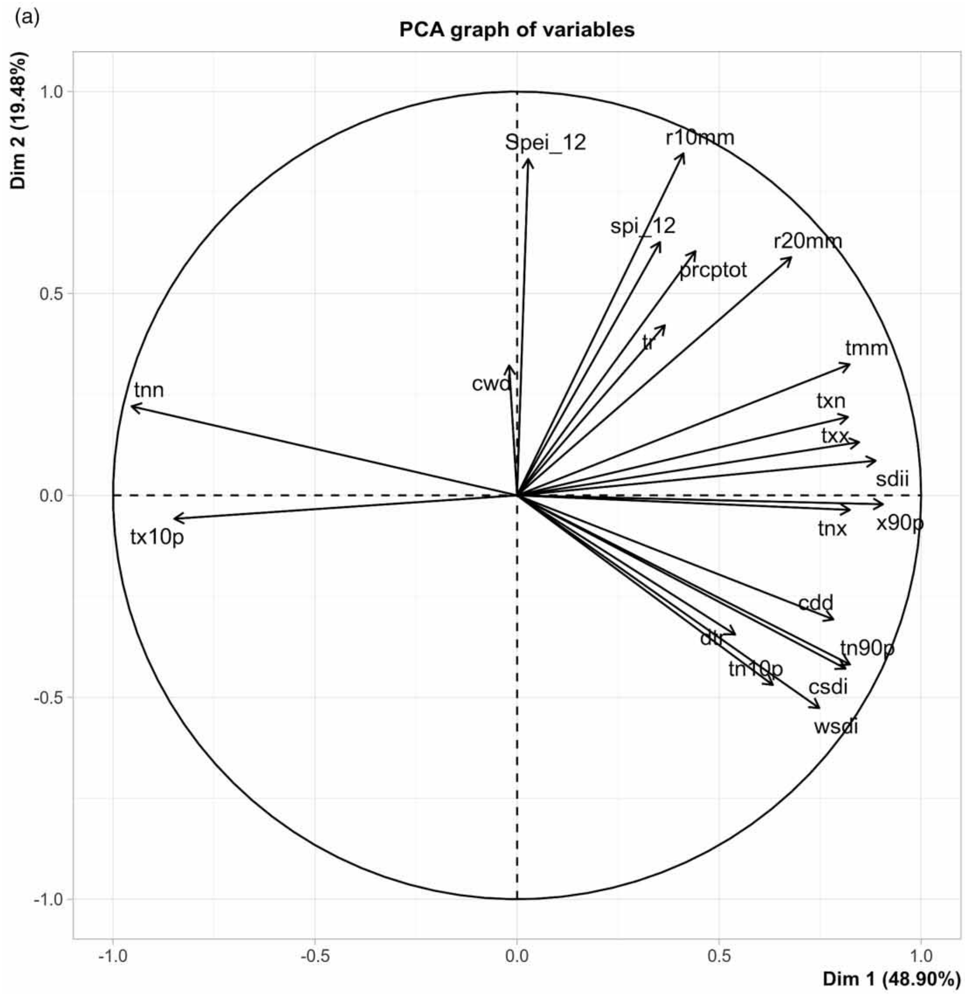
The 2011–2020 decade was the warmest, with a mean temperature of 28.0, 29.38 and 30.2 °C in Sudanian, Sudano-Sahelian and Sahelian zones, respectively (Supplementary Appendix 7). Also, this decade generally experienced the hottest day and night of 1961–2020. This aligned with the warming trends revealed by several climate studies in West Africa (New *et al.* 2006; Barry *et al.* 2018). These findings contrast those of WMO (2013) that indicated the decade 2001–2010 to be the warmest in Africa and even worldwide in all the domains (land, ocean and land–ocean). This contrasting result could be due to the periods of studies: 1901–2010 for the WMO versus 1961–2020 for the current study. Africa experienced warmer than normal conditions every year of the decade 2001–2010 for nearly 94% of reporting countries from WMO's survey (WMO 2013). The coldest decade was not identic across the three climatic zones studied. Indeed, the decade 1961–1970 was the coldest (28.8 °C) in the Sahelian zone while the decade 1971–1980 was instead the coldest in Sudano-Sahelian (28.0 °C) and Sudanian (27.4 °C) zones. These results also differ from that of WMO (2013) that rather indicated the decade 1981–1990 to be the coldest decade on land. The contrasting findings could be due to the spatiotemporal difference in studies scales (global versus local).

Furthermore, the highest frequencies of both warm nights and hot days were not experienced in the same ways across the zones. The 2001–2010 decade was characterised by the highest frequencies of warm nights and hot days in Sudanian and Sudano-Sahelian zones. For WMO (2013), 2001–2010 was a very exceptional hot decade of 1901–2010. The Sahelian zone experienced the highest frequencies of warm nights and hot days during the decade 2011–2020. Similarly, cold extremes did not show the same patterns across zones. The highest frequencies of cool days and cold nights were observed in the Sahelian zone from 1961 to 1970. These frequencies generally were observed from 1971 to 1980 in the Sudano-Sahelian and Sudanian zones.

Generally, the last three decades distinguished themselves by hot climate extremes from the first three decades, mainly characterised by cold climate extremes in all three climatic zones. This aligned with previous research findings (Panda *et al.* 2014).

3.3. Sensitivity of crops to CC across the climatic zones

Climate variability and change have influenced crop production in the study zones (Figure 4). Both positive and negative impacts of climate conditions on the production of the five major crops over the last three decades were observed. Each studied zone presented some specific relationship between crop yields and climate conditions leading to different sensitivity of crop yields to CC. The relationship between yields of the major crops and extreme climate showed differences across the



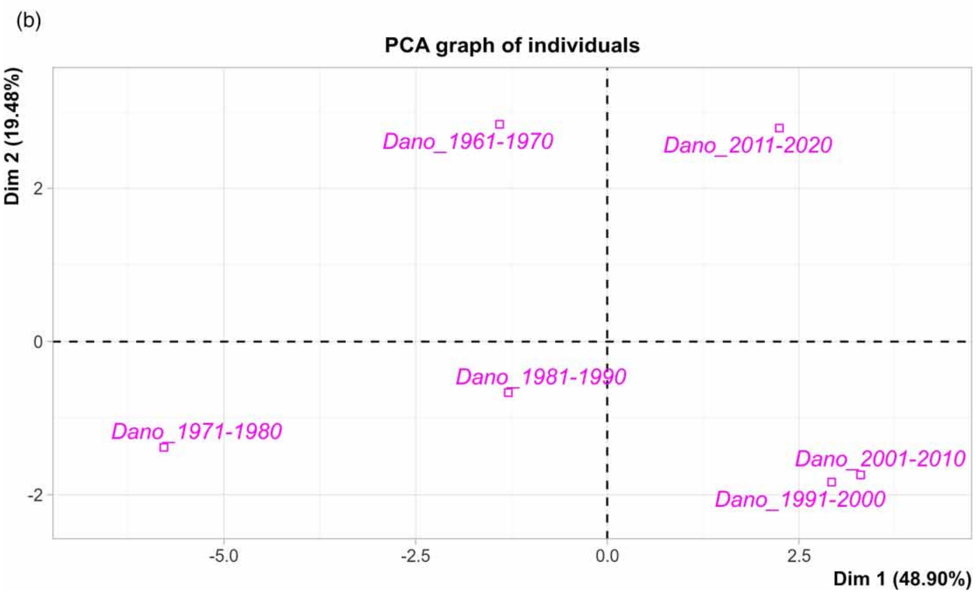


Figure 3 | Decadal trend of rainfall and temperature indices within the Sudan zone (Dano). (a) Graph of variables and (b) Graph of individuals. Component 1 explains 48.9% of the variables and summarises the temperature variables. Component 2 explains 19.5% of the variables and identifies itself to rainfall availability.

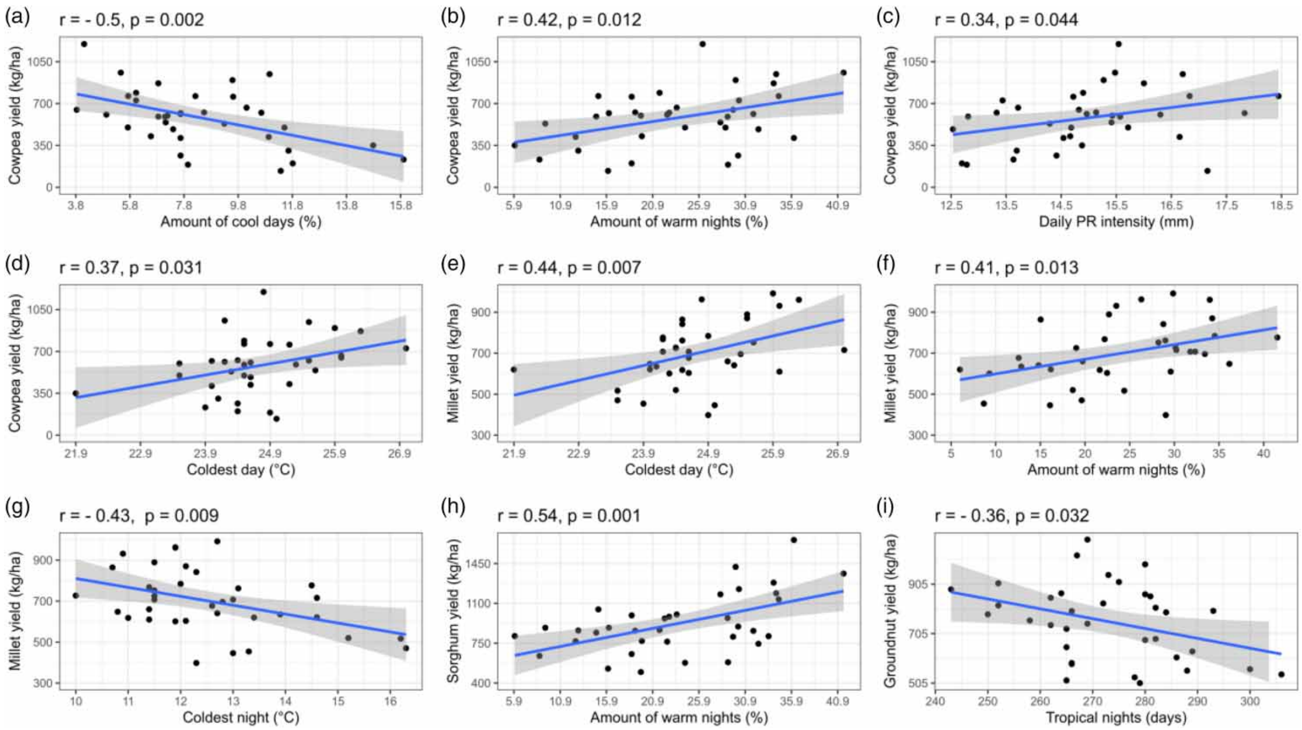


Figure 4 | Bivariate relationship between climate indices and major crop yields in the Sudanian zone.

climatic zones. All the five crops (maize, sorghum, millet, cowpea and groundnut) showed a significant association with extreme climate conditions in all three climatic zones except for maize that showed no significant association in the Sudanian zone at $p < 0.05$ (Figure 4 and Supplementary Appendices 8 and 9).

The multiple linear regression between yields and climate extremes suggested that climate variability and change have different directions of influence (negatively or positively) on crop production (Table 3). Similar findings of this study were reported on cowpea yields in Nigeria during 1961–2006 (Ajetomobi & Abiodun 2010) and in Mali (Butt *et al.* 2005). Furthermore, Waha *et al.* (2013) also reported that CC adversely affected maize production (10–33% yield decrease) in Sub-Saharan Africa, with positive impacts found in mountainous and cooler regions of South and East Africa (6% yield increase). About 67% (14 over 23 indices) of the studied extreme climate indices significantly influenced crop yields across the three climatic zones. Some of these indices adversely impacted yields. This result is congruent with several African authors that similarly revealed the negative implication of climate extremes events on crop germination, growth and production (Abubakar *et al.* 2020). The negative impacts consisted of a severe disruption in plant development through several morphological, physiological, biochemical and molecular changes leading definitely to yield decline (Chadalavada *et al.* 2021). These impacts were found to be more severe within the Sudano-Sahelian and Sahelian zones than the Sudanian zone (Table 3). Crop production in the Sudanian and Sahelian zones was influenced by six and seven climate indices, respectively, while five climate indices affected crop yields in the Sudano-Sahelian zone.

The negative impact of extreme warm indices from this study may not vary much across sub-Saharan Africa due to the continuous rise in temperature on the continent and could alter future food security in Africa and even at a global scale (Chadalavada *et al.* 2021).

3.3.1. Sensitivity of maize to climate extremes across climatic zones

Compared with the other zones, maize production was more influenced in the Sudano-Sahelian zone where both positive and negative influences of extreme climate conditions were observed. A one-unit increase in the coldest night (night warming) and 1 day increase of cold spell duration (day cooling) could have caused a decrease and an increase in maize yield by 85.5 and 50.7 kg/ha, respectively. It seems that night and day temperature trends could affect maize production differently

Table 3 | Effects of climate indices on crop yields across the three climatic zones of Burkina Faso

Models	Coefficient	α	SE	t-value	Pr (>t)	Adj. R^2	p-value
Sudan climatic zone							
Cowpea yield (kg/ha)							
TX10p + R10mm	Intercept	255.9	195.0	1.3	0.199	47.4	**0.000**
	TX10p (%)	−58.4	11.4	−5.1	**0.000**		
	R10mm (days)	22.1	5.5	4.0	**0.000**		
Sorghum yield (kg/ha)							
TN90p + TMM	Intercept	11,242.4	4,967.7	2.3	**0.031**	34.1	**0.000**
	TN90p (%)	24.6	5.8	4.3	**0.000**		
	TMM (°C)	−391.2	181.7	−2.2	**0.039**		
Millet yield (kg/ha)							
TNN + CDD	Intercept	1,465.7	219.1	6.7	**0.000**	23.0	**0.005**
	TNN (°C)	−45.6	15.0	−3.0	**0.000**		
	CDD (days)	−1.6	0.8	−2.0	**0.000**		
Millet yield (kg/ha)							
TXN + R10mm	Intercept	−2,144.7	645.1	−3.3	**0.002**	34.8	**0.000**
	TXN (°C)	97.7	23.7	4.1	**0.000**		
	R10mm (days)	11.8	3.2	3.2	**0.003**		
Sudan-Sahel climatic zone							
Maize yield (kg/ha)							
TNN + CSDI	Intercept	1,733.4	426.9	4.1	**0.000**	29.8	**0.002**
	TNN (°C)	−83.8	32.8	−2.6	**0.016**		
	CSDI (days)	50.7	18.2	2.8	**0.009**		
Groundnut yield (kg/ha)							
TXN + CDD	Intercept	2,589.9	433.9	6.0	**0.000**	44.8	**0.000**
	TXN (°C)	−57.7	15.9	−3.6	**0.001**		
	CDD (days)	−3.4	0.9	−3.9	**0.001**		
Millet yield (kg/ha)							
TNN + R10mm	Intercept	1,099.3	336.4	3.3	**0.002**	39.8	**0.000**
	TNN(°C)	−77.6	21.8	−3.6	**0.001**		
	R10mm (days)	17.8	6.1	2.9	**0.007**		
Sahel climatic zone							
Sorghum yield (kg/ha)							
TX90p + PRCPTOT	Intercept	−1,185.3	137.4	−1.4	0.187	50.2	**0.000**
	TX90p (%)	18.3	4.3	4.2	**0.000**		
	PRCPTOT (mm)	1.2	0.2	5.9	**0.000**		
Cowpea yield (kg/ha)							
TNN + TN10p	Intercept	884.5	462.8	1.9	**0.067**	28.6	**0.005**
	TNN (°C)	−28.6	39.4	−0.7	0.474		
	TN10p (%)	−56.2	16.7	16.7	**0.002**		
Millet yield (kg/ha)							
TN10p + R10mm	Intercept	239.2	129.4	1.8	0.074	33.8	**0.001**
	TN10p (%)	−23.8	11.6	−2.1	**0.048**		
	R10mm (days)	26.7	7.2	3.7	**0.001**		

α, SE and Adj. R^2 represent estimates of regression coefficients, standard error of means and percent adjusted R^2, respectively.
Bold values are significant at $P < 0.05$.

in the Sudano-Sahelian zone of Burkina Faso. Day cooling tends to be favourable to maize production, while the warming trend of the coldest night could have stemmed it. A global-scale study indicated that unusually cold and warm days negatively affect maize yields (Vogel *et al.* 2019).

3.3.2. Sensitivity of millet to climate extremes across climatic zones

A decline in millet yield has been generally observed across all zones due to longer dry spells and climate warming, except in the Sudanian zone where both increased and decreased millet yield trends were observed. A unit warming of the coldest day could have increased millet yield by 97.7 kg/ha, while a one-degree increase in the coldest night (warming of the coldest night) may have caused 45.6 kg/ha reduction in millet yield. Millet yield could have also decreased by 1.6 kg/ha for a 1-day increase in consecutive dry days (dry spell). Such crop failure due to dry climate conditions is highlighted from previous findings (Abubakar *et al.* 2020). In the Sudano-Sahelian zone, millet yield was also declining by 77.6 kg/ha due to a one-degree increase in the coldest night. Finally, in the Sahelian zone, a 1% increase in cold night frequency (nights cooling) causes a decline in millet yield by about 23.8 kg/ha. It seems that millet production has been more sensitive to changes in the night temperature. The negative impact of the changes on millet yield is more pronounced in the Sudano-Sahelian and Sudanian zones than in the Sahelian zone, where such changes were more observed. Furthermore, our findings related to wet extreme climate indices are in line with research that indicated crop failure is favoured by a decline in rainfall (Abubakar *et al.* 2020) while rain resumption is potentially favourable to crop yields. Indeed, heavy rain days favourably increase millet yield by 11.8, 17.8 and 26.7 kg/ha in Sudanian, Sudano-Sahelian and Sahelian zones, respectively.

The warming trend in the zone might have offset to some extent the observed favourable effects of rain on millet yields (Wheeler *et al.* 2000; Panda *et al.* 2014; Abubakar *et al.* 2020). Indeed, hot temperatures at the time of flowering can reduce the potential number of seeds or grains formed or developed (Wheeler *et al.* 2000).

3.3.3. Sensitivity of sorghum and groundnut to climate extremes across climatic zones

Suppose sorghum production could have been drastically affected by the average temperature (yield decline of 391.2 kg/ha due to one-degree increase in average temperature) in the Sudanian zone. In that case, this crop production seems rather to have been favoured by changes in hot climate extremes in the Sudanian and Sahelian zones of the country. Indeed, a unit increase in warm nights (nights warming) in the Sudanian zone could have increased sorghum yield by 24.6 kg/ha. Furthermore, a 1% increase in hot days (day warming) in the Sahelian zone could have induced an increase (by 18.3 kg/ha) of sorghum yield. Thus, the present stade of climate warming seems to have been favourable to sorghum production in the abovementioned zones.

Moreover, a millimetre increase in the total precipitation could have induced sorghum yield increase by 1.2 kg/ha in the Sahelian zone. The Sudano-Sahelian zone did not show significant impacts of climate indices on Sorghum yield. Groundnut yield was also observed to be negatively associated with the coldest day and consecutive dry days. A yield decline by 57.7 and 3.4 kg/kg could have been observed in the zone due to a degree and a day increase in the coldest days and dry spell, respectively.

Groundnut production was seriously threatened only in the Sudano-Sahelian, while Sorghum was the less disturbed crop by extreme hot days and nights temperature. The results could be due to the warm-weather crop nature of the Sorghum (Du Plessis 2008).

3.3.4. Sensitivity of cowpea to climate extremes across climatic zones

Cowpea yield seems to have been more affected in the Sudanian and Sahelian zones, particularly, by cold climate extremes (cool days and cold nights). Indeed, a one-unit increase in cool days (day cooling) within the Sudanian zone could have reduced cowpea yield by 58.4 kg/ha. Inversely, a degree increase in the coldest night (warming of the coldest night) and a 1% increase in cold nights (night cooling) frequency could have caused a reduction of 28.6 and 56.2 kg/ha, respectively, in cowpea yield. The findings were consistent with Panda *et al.* (2014) that attested that the extreme state of day and night temperatures adversely impact major crops through changes in phenological development and physiological processes. Night and day cooling is thus unfavourable to cowpea production in the Sudanian and Sahelian zone of Burkina Faso. Despite the increased trend of hot climate extremes experienced within each climatic zone, these extremes did not negatively influence cowpea production. This result did not support the claim that hot temperatures during flowering can reduce the potential number of seeds or grains yield and stem growth (Wheeler *et al.* 2000). The drought-tolerant nature of cowpea varieties (Agossou *et al.* 2020) may be an explanation.

3.4. Crop yields variations across climatic zones

Generally, the study found that the extreme climate indices explained almost one-quarter to half of the variability in crop yields (maize, groundnut, cowpea, sorghum and millet) across the study zones. In all the zones, the adverse impacts of climate extremes were more observed than their positive influences on crop yields. In Sudanian and Sudano-Sahelian zones, the average temperature and rainfall over the study period (1984–2020) were in the range required for crop's optimal growth (27–30 °C and 400–1,200 mm/y) (Du Plessis 2008; Hatfield *et al.* 2011; Agossou *et al.* 2020). Nevertheless, yields were significantly affected by changes in extreme climate conditions. This means that climate extremes (cold days and nights, warm nights, coldest days and tropical nights) more than changes in the average climate conditions are responsible for observed variation of crop yield in the study zones (Vogel *et al.* 2019).

Moreover, in the Sahelian zone, despite the persistence in some years (after 2005) of average daily temperature (Supplementary Appendix 2) beyond the required maximum temperature (30 °C) for the majority of crop growth (Du Plessis 2008; Agossou *et al.* 2020), no significant interrelation was observed with some of the studied crops. This further supports that climate extremes (hottest days and nights, frequency of cold nights) are more responsible for crop yield variations. Furthermore, as indicated by Vogel *et al.* (2019), our findings revealed that temperature-related extremes are more responsible for yield anomalies than precipitation-related extremes.

Changes in extreme climate conditions have explained between 21–47 and 29–50% of the variation in crop yields within Sudanian and Sahelian zones, respectively, and about 30–45% of the variation in crop yields within the Sudano-Sahelian zone. Consequently, this underlines the possible important role played by non-climatic factors in crop yield determination. Therefore, about 53–79 and 50–71% of crop yield variation in Sudanian and Sahelian zones, respectively, then about 55–70% of yields variation in the Sudano-Sahelian zone may be attributed to non-climatic factors such as improved seed, fertility of the soils and farming methods, among others (Atiah *et al.* 2021). These authors suggested in their research a need to study the impacts of non-climatic factors on maize yield to maximise its production in Ghana. This suggestion is paramount for Burkina Faso and SSA agriculture sector as well. Therefore, more efforts at policies and research levels must be done to discriminate between climatic and non-climatic impacts, thus allowing a better understanding of non-climatic factor's impact on yields, including soil fertility, seeds and farmers' practices.

The observed variations in crop yields attributable to extreme climate indices are lower than the value reported at a global scale by Vogel *et al.* (2019). According to these authors, climate extremes indices account for more than half of the explained variances of yield anomalies (maize, rice, soybeans) and nearly half of spring wheat at the global scale. The findings may be attributed to differences in crop types and climate conditions of the respective studied zones.

4. CONCLUSION

The current study found evidence of change and variability in rainfall and temperature patterns in the study areas. However, the change is much more pronounced in temperature than in rainfall, at all scales of assessment. Moreover, the study revealed that hot extremes indices are evolving much faster than their counterpart cold extremes within the study zones, witnessing a warming climate across the three climatic zones studied. Decadal climate indices analysis showed that the last three decades in each climatic zone distinguished themselves by hot climate extremes from the first three decades that were generally characterised by cold climate extremes. Likewise, recent decades of the assessed period (1961–2020) were wetter. The warming climate and rainfall variability experienced within the study zones pose more stress for crops productions, thereby threatening the livelihoods of farming households in such zones. The induced threats led to crop yield reduction. The Sudano-Sahelian and Sahelian zones, where CC was more pronounced, are likewise more exposed to such threats. Across all three zones, crop yields were significantly associated with some climate indices. It can be deduced that climate variability and CC highlighted through indices trend in the current study is affecting the climate-dependent agricultural sector in Burkina Faso and could affect farmers' livelihoods. The major crops (maize, groundnut, cowpea, sorghum, millet) produced within the study zones responded differently (positively and negatively) to climate extremes indices. They were found to be more sensitive to these extremes than the average climate conditions.

A climate-smart policy option consisting of monitoring and/or addressing climate impacts could harness certain indices' positive influence (yield increase) on crops or mitigate adverse effects (yield decline) of other indices. Mitigation could consist of breeding more resilient crops and adopting a crop-livestock integration practices to enhance the livelihood of smallholder farmers in Burkina Faso.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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