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RESEARCH

Spatiotemporal relationships between rainfall indices and crop yields in the Sudano-Sahelian zone of Cameroon

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Abstract

In the Sudano-Sahelian zone of Cameroon, agriculture — predominantly rainfed — constitutes a major economic sector, underpinning food security but remaining vulnerable to rainfall variability. This study explores statistical relationships between 25 rainfall indices and the yields of maize (*Zea mays* L.) from 1999 to 2021 and cotton (*Gossypium hirsutum* L.) from 1991 to 2010, employing Pearson correlation tests across temporal and spatial scales. At the temporal scale, results indicate that maize and cotton yields respond similarly to two indices: the end of the rainy season (EOS) and cumulative dry spells (CDS15). A longer rainy season is associated with higher yields for both crops, whereas dry spells exert a negative influence across the entire study area. However, spatial analyses reveal significant local variations in crop responses. Specifically, maize yields exhibit positive correlations with indices such as rainfall amount (PRCPSEAS), rainy days (R1mm), wet days (R20mm), season length (SL) in the northern and southwestern parts of the study area, reflecting the importance of consistent moisture availability for optimal growth. Conversely, cotton yields are strongly negatively correlated with these same indices in the northern, northwestern, central, and southeastern parts, likely reflecting the crop's lower tolerance for excessively humid conditions. The findings highlight the need for crop-specific adaptation strategies to rainfall variability, including the selection of appropriate crop varieties, adjustments to planting calendars, improved water management practices, particularly in the context of increasing rainfall trends. Policymakers could invest in localized agro-climatic forecasting systems and improve the integration of climate data into agricultural advisory services.

Keywords Northern Cameroon · Rainfall indices · Maize · Cotton · Yield

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1 Introduction

Agriculture is the mainstay of the Cameroonian economy (Tingem et al. 2008). Most importantly, this sector is also responsible for providing food security to both rural and urban populations from domestic production. In Cameroon's Sudano-Sahelian zone, rainfed agriculture and livestock farming are critical to food security and income generation for much of the population (Guibert et al. 2003; MINEPAT 2017). The region's vulnerability stems from its dependence on rainfall, making the local communities particularly sensitive to climate variations. Despite this context, cotton (*Gossypium hirsutum*) and maize (*Zea mays* L.) have emerged as staple and cash crops respectively. Cotton is the leading cash crop; its products are marketed through the state-run Cotton Development Company (SODECOTON) (Missé 2019). Maize, a staple food crop, plays a central role in ensuring food security for both rural and urban populations

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(Mbah et al. 2023). It is also the principal raw material for food processing, brewery, livestock feed, and agro-based industries throughout the country (Mbah et al. 2023).

However, these two crops have rather different ecophysiological needs: cotton is a heliophilous crop that requires substantial sunlight and approximately about 500 mm of water during its cropping cycle, from planting to at least cut-out stage (Loison 2015). Maize is highly sensitive to drought, rainfall amount and distribution, especially during germination, flowering, and grain filling stages (Yasin et al. 2024), and requires at least 600 mm of well-distributed rainfall during its cycle (CIRAD 2003). In northern Cameroon, cotton and maize are grown in an intensive cropping system using conventional soil tillage, mineral fertilization, application of insecticides and improved varieties (Baboulé and Roose 1998; Diallo et al. 2008). Cotton and maize are often grown in rotation within the cotton-maize-groundnut cropping system (Missé 2019). One of the most important benefits of applying crop rotation is to prevent the spread of pests, weeds, and diseases through rotating the crops, where inclusion of breaking phases decreases its population dynamics (Zohry and Ouda 2018). Crop rotation as a practice, helps also to improve the physicochemical characteristics of soil, with a view to promoting water infiltration, reducing runoff, erosion and soil compaction; and restoring soil fertility through organic matter intake (Tchuenga et al. 2024). These agricultural activities are supported by key structures such as the Institute of Agricultural Research for Development (IRAD), SODECOTON and the Ministry of Agriculture and Rural Development (MINADER). Cotton, the sole industrial crop in the north and far north regions of Cameroon, holds significant economic importance (Fok et al. 2019), and its rotation with maize and groundnut has led to the development of an integrated cropping system (Missé 2019).

However, climate change and climate variability influence crop production in northern Cameroon and contribute to exacerbating poverty and social unrest (Njoya et al. 2022). Climate change, especially rainfall, are predicted to affect crop growth conditions (Sultan et al. 2009; Gérardeaux et al. 2013, 2018). Increased variability in seasonal rainfall patterns, along with more frequent extreme weather events such as droughts and heavy rains, threatens the region's resilience (Field et al. 2012; Molua 2006). These climatic events cause disruptions in agricultural productivity, increase food insecurity, and intensify human migration (Beauvilain 1996; Tamoffo et al. 2023).

Rainfall regimes in Cameroon's Sudano-Sahelian zone are characterized by variability (Banga et al. 2019), with fluctuations in duration, frequency, and amount across meteorological stations (Amougou et al. 2015). The variability in the rainy days, along with heavy rainfall, directly influences vegetation productivity across the Sahelian zone (Zhang et al. 2018). Recent studies also suggest a trend of increasing average annual rainfall in northern Cameroon (Bouba et al. 2017; Vondou et al. 2021), accompanied by a delayed onset of the rainy season and an increase of rainfall amount (Njouenwet et al. 2022).

Agricultural production in the northern Cameroon has been described as highly sensitive to these trends, with yields vulnerable to both rainfall distribution and extreme climatic events (Sultan et al. 2009). Besides, M'biandoun and Olina (2006) revealed that insufficient water supply for crops leads to low agricultural production in Cameroon's Sudano-Sahelian zone, although they did not quantify the extent of yield reductions. Njouenwet et al. (2021a, b) identified significant drought trends during maize and groundnut cropping periods in the southwestern part of the study area. They found that high and very high drought risk zones were concentrated in the north, central, and southeastern parts of Cameroon's Sudano-Sahelian zone. However, their study did not establish a direct link between rainfall and maize yields in the region.

Sultan et al. (2009) demonstrated that early or late season rainfall deficits can shorten the rainy season, negatively affecting cotton yields. Njouenwet et al. (2021a, b) identified that average cotton yield in northern Cameroon aligns with seasonal rainfall indices such as the end date of the rainy season, annual rainfall amount, and the number of rainy days, whereas it has an inverse relationship with the onset date.

For maize production, Obour et al. (2022) demonstrated that erratic rainfall, characterized by delays, shorter rainy seasons, prolonged droughts, and pest infestations led to significant maize yield reductions between 40% and 70% in Ghana in 2020. Lawal and Adesope (2021) also found that maize yields are highly vulnerable to climate variations across most growing areas. In Cameroon's northern region, Epule et al. (2021) identified maize as the most vulnerable cereal, due to rainfall and temperature variability. Tume and Ngwa (2021) discovered the impact of rainfall variability on maize production between 1990 and 2015 in the Ndop plain, Bamenda. A more recent study by Tume et al. (2024) which expanded the study area to include four localities, highlighted decreasing maize yields in Ndu (2000–2021), Oku (1982–2018), and Nkum (2001–2020), while yields in Ndop continued to rise up between 1990 and 2018.

Despite the wealth of existing research on links between rainfall patterns and crop yields, relatively few studies have specifically focused on Northern Cameroon, including Yaouba et al. (2024); Njouenwet et al. (2021a, b, 2022); Gérardeaux et al. (2013, 2018); Sultan et al. (2009). Also, the relationships between specific rainfall indices and the yields of both maize and cotton remains largely understudied, despite the importance of these two crops in the region.

That is why this study proposes to investigate relationships between rainfall indices and the yields of maize and cotton at the divisional and sector scales respectively in the Sudano-Sahelian zone of Cameroon, with the aim of understanding the impact of rainfall regimes on crop yields. Three hypotheses are tested: (i) certain rainfall indices are significantly correlated with the yields of both maize and cotton, (ii) certain rainfall indices exhibit significant correlations with maize and cotton yields in the same direction, and (iii) the relationships between rainfall indices and crop yields vary depending on the periods and locations. To test these hypotheses, Pearson correlation tests will be employed. The following sections present the study area, the data used, and the methods applied, before discussing the results.

2 Materials and methods

2.1 Study area

The Sudano-Sahelian zone of Cameroon (7°-13°N, 12.20°-15.70°E), is predominantly composed of lowlands interspersed with isolated mountain ranges (MINEPAT 2022). Its climate, characterized by a unimodal rainfall regime, can be divided into two distinct zones: the Sahelian region, to the north of 10° N and between 13° and 15,70°E; with a semi-arid climate, and the Sudanian region to the south (7°-10°N, 12°-15°E), with a tropical savanna climate (Fick and Hijmans 2017, National Geographic Society 2024). Both zones experience alternating wet and dry seasons driven by the dynamics of the African monsoon, and their hydrology is marked by seasonal rivers, locally known as mayos, which can overflow and cause flooding during the rainy season (Bouba et al. 2017). Rainfall varies significantly across both zones, from 400 mm per year in the northern Sahelian area to 1,400 mm per year in the southern Sudanian area, while average yearly temperatures range from 28 °C to 34 °C per year (Dassou et al. 2016). Administratively, the Sudano-Sahelian zone encompasses the North region (65,756 km²) and the Far-North region (34,262 km²), including ten divisions and sixty-eight subdivisions. The main crops include maize, cultivated across the entire zone, and cotton, restricted to the "cotton belt" located between latitudes 7.50° and 11.50° N. The divisional scale refers to an administrative unit in Cameroon, which is a level below the "regions". Specially, they are called "divisions", and the study area counts 10 of them with each division having an average area of 10,024 km². The sector level refers to a zoning system established by SODECOTON to divide cotton production areas. This zoning is based on the agroecological criteria of production units rather than administrative boundaries. Each sector covers an average area of 1,832 km² (see Fig. 1).

2.2 Rainfall data

This study uses daily interpolated rainfall maps, produced from a compendium of daily rainfall observations (https://doi.org/10.5281/zenodo.10156437) presented and analyzed in a publication to come (Knops et al. in preparation.), using ordinary kriging. These maps available on Zenodo repository at the DOI https://doi.org/10.5281/zenodo.11067784, cover the period from 1948 to 2022 with a spatial resolution of 0.01°, corresponding to pixel sizes ranging from 1.19 to 1.22 km² for latitudes between 6°N and 13°N and 11°E-15.70°E of longitudes, encompassing the entire Northern Cameroon region. A significant portion of the rainfall observation data used comes from SODECOTON, whose records are, however, limited to the rainy season, spanning from March to October, and exclude rainfall data during the dry season.

From these daily rainfall maps, various annual rainfall indices, including wet spell (WS) and dry spell (DS) indices, were calculated by Knops et al. (in preparation) (Table 1) following the methodology outlined in Fall et al. (2019). Notably, the methodology used to define the onset (start of season, SOS) and the retreat (end of season, EOS) dates of the rainy season were derived using the method developed by Liebmann et al. (2012), where for each grid point the sum of the daily rainfall minus the climatological annual daily average is calculated. The day after the absolute minimum marks the onset date, indicating the start of consistent above-average precipitation. The maximum in this value establishes the retreat date, indicating the transition to below-average precipitation. Once the onset and the retreat dates are known, the rainy season (season length, SL) is defined as the period between these two dates. These indices and many others as defined in Table 1, will be used for analyzing the seasonal distribution of rainfall and its relationships with cotton and maize yields.

2.3 Crop yield data

This study uses yield information for two important agricultural productions in the North and Far North regions of Cameroon, maize and cotton.

Maize yield data were mostly collected from the Statistical services of the regional delegations of the Minister of Agriculture and Rural Development (MINADER) in the North and Far-north regions of Cameroon. This was completed by information from AGRISTAT reports (MINADER 2002, 2004, 2006, 2007, 2008, 2009, 2010, 2012), a national

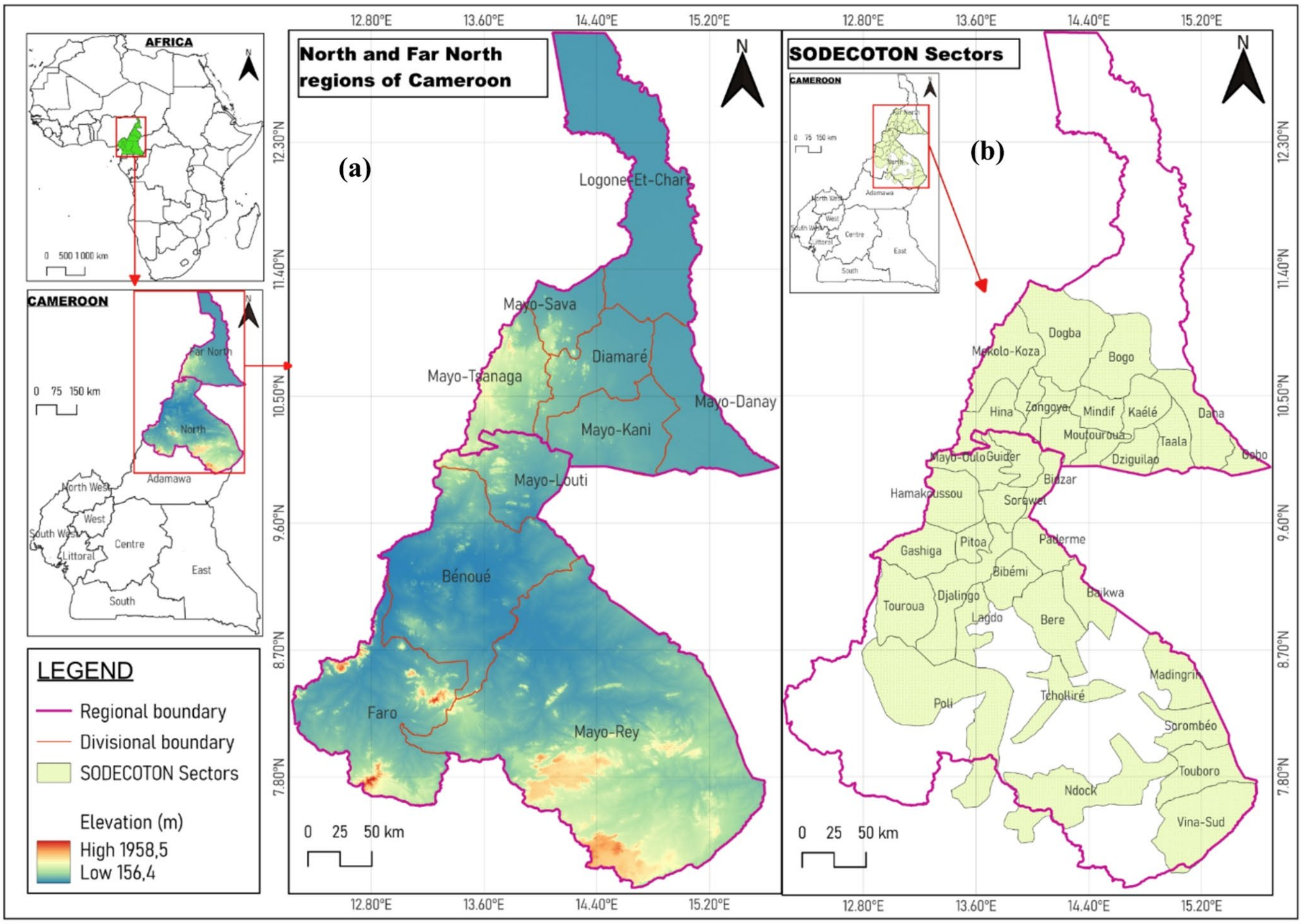

Fig. 1 Study area. The two maps focus on the North and Far North regions of Cameroon. Map (**a**) shows the divisional boundaries, corresponding to the scale of maize yield data, while map (**b**) shows the cotton-growing sectors

agricultural statistics yearbook. The collected data represent aggregated average values at the divisional scale, initially gathered at the sub-divisional and agricultural post scales. The data cover annual divisional yield estimations on the period from 1999 to 2021 with $N=230$ annual yield observations (10 divisions x 23 years). This dataset is described in detail in supp Table 1 and was cleaned by removing years with insufficient data. Notably, four divisions lacked yield data for the year 2015, leading to a reduction of the total sample size from 230 to 226 observations.

The cotton yield data results from a compilation work carried out by Leblois et al.(2014) as a part of their study about the potential of weather potential of weather index-based insurance to mitigate risk for cotton farmers. It is based on cotton yield calculated from declared surfaces and measured cotton production at the scale of cotton production sector level in kg/ha provided by SODECOTON. It is an aggregation of data from the producer groups' level used for the internal accounts of the SODECOTON. As the company is the only buyer and the only input provider in Cameroon, it is an exhaustive database of the cotton producers in the country (Leblois et al. 2014). This dataset covers 43 sectors over a 28-year period, from 1983 to 2010. For the operational use of the cotton dataset, data preparation was carried out. Since the years 1984, 1986–1987 and 1989–1990 were missing, the choice was made to only keep the data between 1991 and 2010, to ensure accurate and reliable results. Ultimately, only 37 sectors were retained with $N=740$ annual yield observations (37 sectors x 20 years), as data from 6 sectors had to be excluded due to changes in SODECOTON's sector boundaries. *Nan* values and duplicate lines were removed, reducing the total sample size from 740 to 605 observations. This cleaning process resulted in a sector dataset in shapefile format covering 37 sectors over a 20-years period from 1991 to 2010.

Table 1 Definition of rainfall indices used in this study

Rainfall index	Description	Symbol
Seasonal indices	Seasonal rainfall onset (start of season, SOS) and cessation (end of season, EOS) calculated using the cumulative daily mean rainfall anomaly method (Liebmann et al. 2012), season length (SL) calculated as the difference between cessation and onset dates (day of year, DOY)	SOS, EOS, SL
Seasonal total precipitation	Sum of precipitation during the rainy season (March-October) (mm)	PRCPSEAS
Rainy days	Number of days with rainfall > 1 mm (days)	R1mm
Relative rainy days	Percentage of rainy days during the rainy season (%)	RRD
Wet days 20/30/40/50	Number of days with rainfall > 20/30/40/50 mm (days)	R20/30/40/50 mm
Relative wet days 20/30/40/50	Percentage of wet days with > 20/30/40/50 mm of daily rainfall during the rainy season (%)	RWD20/30/40/50
Cumulative wet spells 10/15/20 (90p)	10/15/20 days with rainfall > 90th percentile of daily rainfall (number of events)	WSC10/15/20 (90)
Heavy rainfall days	Day with rainfall > 90th p of daily rainfall (days)	R90p
Dry days	Number of days with daily rainfall < 1 mm (days)	DD
Relative dry days	Percentage of dry days during the rainy season (%)	RDD
Cumulative dry spell 10/15/20	10/15/20 days with less than 10/15/20 mm of rainfall (number of events)	CDS10/15/20
Long dry spells	8–14 consecutive dry days (number of events)	DSL
Extreme long dry spells	Consecutive dry days exceeding 15 days (number of events)	DSxL

2.4 Exploration of links between rainfall indices and maize and cotton yields

2.4.1 Data Preparation

To explore the statistical relationship between rainfall indices and maize and cotton yields, a series of data processing steps were performed using Python (version 3.10) with several libraries. Initially, typographical errors in the names of geographical entities were harmonized across the different maize and cotton yield datasets and shapefiles using the Levenshtein distance function.

The rainfall indices and the divisions and sectors shapefiles datasets were projected into the same geographic coordinate system (EPSG:4326, WGS84) using the *rioxarray* library. We then applied a spatial aggregation function, which involved calculating the mean rainfall indices for each division for maize and each sector for cotton using the *numpy.mean* function. Simultaneously with the aggregation of rainfall indices, we integrated the average maize and cotton yield data into the divisions and sectors dataframe. Finally, once the data were aggregated, we proceeded to explore the statistical relationships between the precipitation indices and crop yields.

2.4.2 Statistical tests

Declared yields were then correlated with each average rainfall index using Pearson correlation tests, which returned the Pearson correlation coefficient and the corresponding p-values. For each combination of rainfall index and crop yield (cotton or maize), the Pearson correlation coefficient (r) quantifies the linear relationship between the rainfall index and cotton or maize yield, reflecting the degree to which both variables vary together.

The value of r ranges from −1 to +1, where +1 indicates a perfect positive linear relationship, -1 indicates a perfect negative linear relationship, and 0 indicates no linear association (Nettleton 2014). The associated p-value indicates the statistical significance of the correlation, a p-value threshold of 0.05 was deemed relevant for this study.

2.4.3 Temporal and Spatial aggregation

Throughout the analysis, two types of data aggregation: temporal and spatial were applied. Aggregation, in this context, refers to the grouping of rainfall indices and yield data for maize and cotton based on their averages along a given scale. This method helps to identify overall patterns in the statistical relationship between rainfall indices and crop yields. Temporal aggregation involves averaging data over time, specifically across all years for the entire study area. This method smooths out interannual variability in indices and yields, providing a synthesized view. Spatial aggregation, on the other hand, entails averaging indices and yields across the divisional scale for maize and sector scale for cotton. This approach takes into consideration the spatial variability in rainfall indices and crop yields, which might otherwise be influenced by the unique local conditions of each division or sector.

3 Results

This section presents the main findings on the relationships between rainfall indices and the yields of two major crops in northern Cameroon, maize and cotton. The results are structured to reflect the different scales of analysis beginning with a general presentation of rainfall indices and crop yields patterns, before analyzing their relationships at different scales– temporal and spatial– highlighting shared crop responses to rainfall indices.

3.1 Presentation of rainfall indices and crop production

Correlation analysis served to estimate the relationship between the rainfall indices and the crops yields (maize and cotton).

This study identified five indices that were significantly correlated with both maize and cotton yields in the study area (RRD, R30mm, RWD30, R40mm, R90p). Among these indices, the RRD (Fig. 2a and b), showed correlations in opposite directions in between the two crops: while maize yields displayed a weak positive correlation with RRD ($r=0.15$), cotton yields were weakly and negatively correlated ($r = -0.12$). This suggests that an increased proportion of rainy days supports maize production, whereas excessive rainfall days may hinder cotton production.

Furthermore, four of the five common rainfall indices (R30mm (Fig. 2c and d), RWD30 (Fig. 2e and f), R40mm (Fig. 2g and h), and R90p (Fig. 2i and j)) were positively correlated with yields, though the strength of the correlations remained modest. This confirms the consistency of the relationship between rainy periods and maize or cotton production in northern Cameroon. Specifically, an increase in the proportion of rainy days with more than 30 mm of daily rainfall over the rainy season appears to improve yields for both crops. Despite differences in the agronomic practices and distinct temporal scales of the datasets, notable similarities emerge in how the two crops respond to rainfall patterns. These convergences may reflect shared adaptive mechanisms to the irregular rainfall patterns of northern Cameroon. However, the divergences, particularly those observed for the RRD index, underscore the need for differentiated strategies to optimize yields according to the specific requirements of each crop.

In addition to these principal results, supplementary Table 3 (crop– no aggregation) presents the correlation matrix between the 25 rainfall indices and maize and cotton yields. For each crop, 12 indices show statistically significant correlations with yield. For maize, the indices significantly correlated with yield are mostly related to wet conditions: positive correlations are observed with SL ($r=0.30$), R1mm ($r=0.27$), PRCPSEAS ($r=0.21$), R90p ($r=0.23$). In the case of cotton, positive correlations are also found with some rainfall indices linked to wet conditions such as RWD30 ($r=0.18$), RWD40 ($r=0.19$)– though these correlations are generally weaker than those observed for maize except for the R90p index, which exhibits a moderate positive correlation ($r=0.30$). Additionally, cotton yields are positively and weakly correlated with certain indices indicative of drier conditions, such as DD ($r=0.14$).

The results of the exploratory analysis, while indicative of certain trends, revealed relatively weak correlation coefficients between rainfall indices and the yields of both crops. This suggests that, although relationships do exist, they remain modest when the data are analyzed in their raw form. This can be attributed to the natural variability of rainfall at the local scale and the diversity of agronomic and environmental factors influencing yields.

3.2 Temporal relationship between rainfall patterns and crop yield

The results obtained from the temporal aggregation of rainfall indices and maize and cotton yields revealed stronger correlations compared to those observed in the exploratory analysis. This aggregation led to an increase in the number of significant relationships between rainfall indices and crop yields, particularly for cotton yields. For cotton, 21 out of the 25 rainfall indices showed significant correlations with yield (Supp Table 3– crop temporal aggregation). Among these, two indices (EOS and CDS15) were significantly correlated both with maize and cotton yields.

The EOS (Fig. 3a and b) shows a strong positive correlation with the yields of both crops, with identical correlation coefficients for maize and cotton ($r=0.66$). This suggests that a lengthening of the rainy season, particularly the delayed end of rainfall beyond the average duration, may be beneficial for the yields of both crops. This relationship may be linked to the need for crops to receive sufficient humidity towards the end of the season, especially in a region where rainfall was unevenly distributed. However, this delayed end of the rainy season must be accompanied by a regular distribution of rainfall, as prolonged dry spells even within a longer rainy season, can have negative effects on crop yields. Indeed, a delayed end of the rainy season does not necessarily imply a reduction in dry spells. It is possible that within the same rainy season, multiple dry spells may occur while observing an overall extension of the rainy season itself.

In this sense and in contrast, the CDS15 (Fig. 3c and d), shows a strong negative correlation with the yields of both crops. This relationship suggests that an increase in dry spells, or prolonged periods without significant rainfall, is correlated to yield decrease. However, this effect seems more pronounced for maize than for cotton, as reflected in their respective correlation coefficients ($r = -0.65$ for maize and $r = -0.45$ for cotton). This could reflect maize's particular

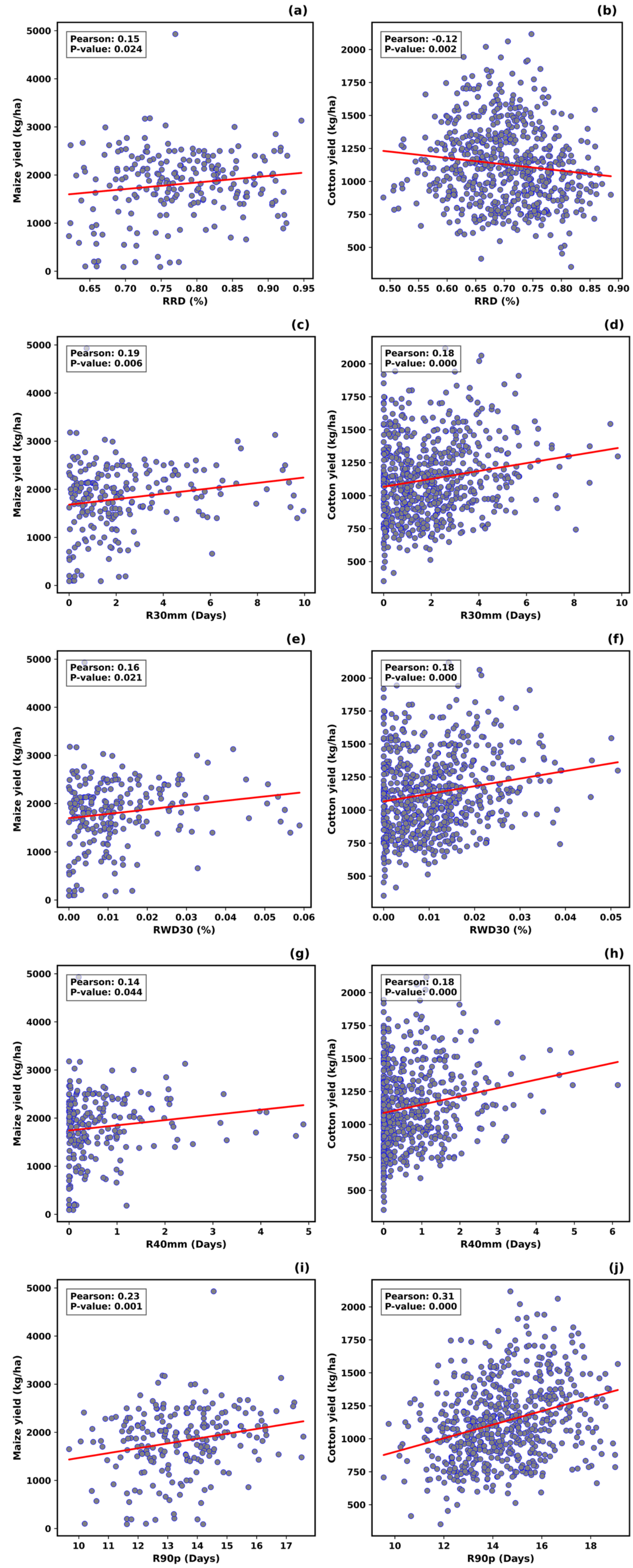

Fig. 2 Relationship between rainfall indices and both crops (maize and cotton columns 1 and 2, respectively). RRD versus crop yields (**a**, **b**), R30mm (**c**, **d**), RWD30 (**e**, **f**), R40mm (**g**, **h**), R90p (**i**, **j**). For each culture, blue dots represent the yields of each sector and division per year

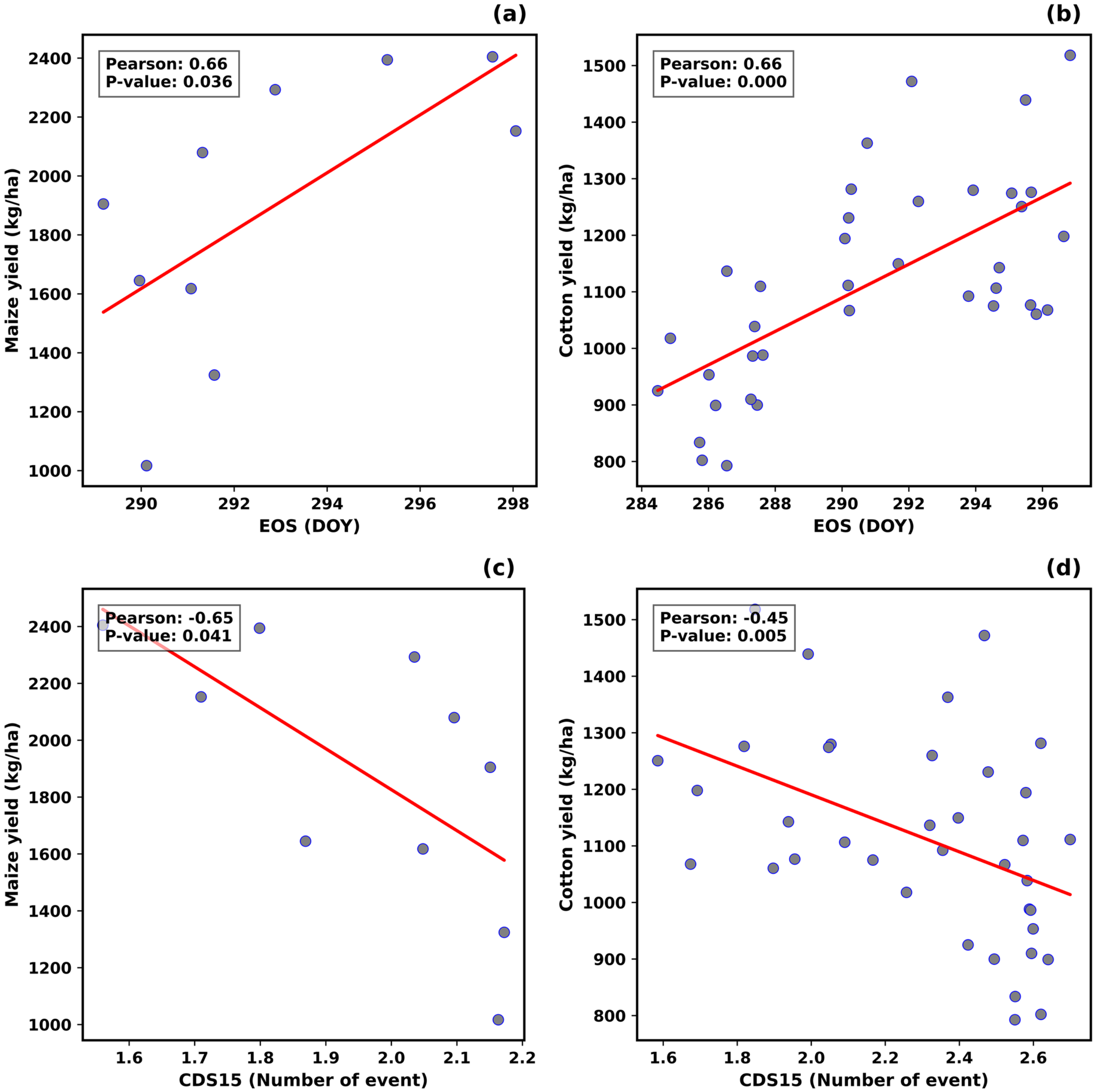

Fig. 3 Temporal aggregation for rainfall indices and both crops (maize and cotton columns 1 and 2, respectively). EOS vs. crop yields (**a**, **b**), CDS15 (**c**, **d**). Blue dots represent aggregated indices and yields at the divisional scale for maize, and sector scale for cotton for all the years. The red line represents the regression line

sensitivity to prolonged dry spells, given its higher water requirements during its development phases.

3.3 Spatial relationship between rainfall patterns and crop yield

The spatial analysis revealed that 13 out of 25 rainfall indices were correlated with maize yields, while 16 indices were correlated with cotton yields. Among these, 8 indices were common to both crops, indicating shared relationship.

Maize yields show a positive correlation with indices indicative of wet conditions, such as EOS, SL, R1mm, PRCPSEAS, R20mm and R30mm (Fig. 4c, e, g, i, k, m respectively). These relationships suggest that prolonged rainy periods or more frequent precipitation generally enhance maize yields in certain divisions.

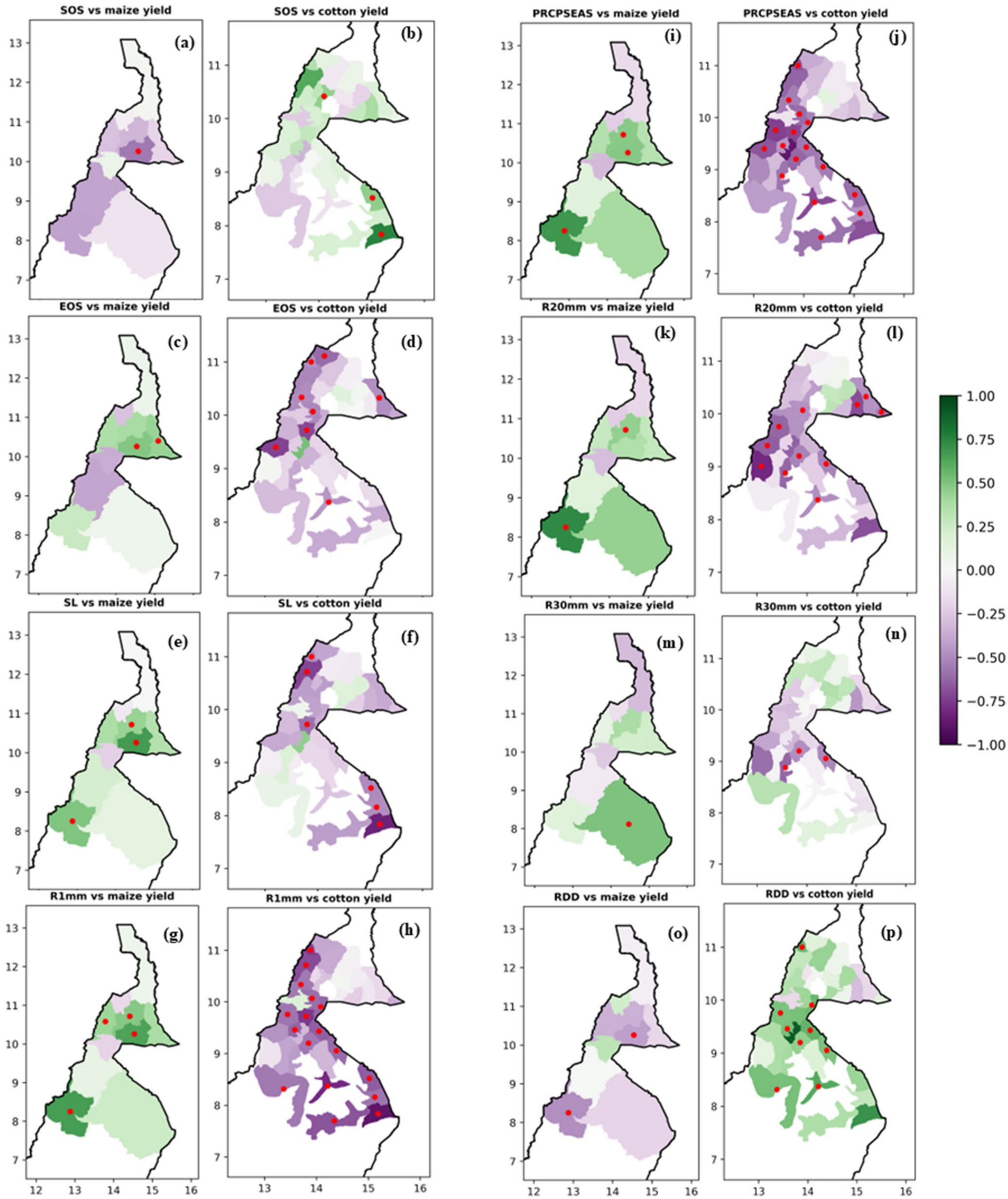

Fig. 4 Spatial correlation between rainfall indices and maize (first and third columns) and cotton (second and fourth columns) yields. The violet and green colors represent, respectively, the negative and positive correlation over each division (maize) and sector (cotton). The red dots indicate statistical significance at p-value < 0.05. The scale bar illustrates the Pearson correlation coefficients

However, the relationship of these indices with maize yields varies by divisions. For instance, the EOS and SL indices are positively correlated with maize yields in the northeastern and southwestern parts of the study area (Fig. 4c and e), despite the negative correlation of SOS. Similarly, indices such as R1mm, PRCPSEAS, and R20mm exhibit significant correlations in northern and southwestern zones, while R30mm is significant only in the southeastern zone. In contrast, the RDD index shows a negative correlation. These negative relationships (SOS, RDD) indicate reduced maize yields when rain starts late (Fig. 4a) or when the proportion of dry days increases (Fig. 4o) in the northern and southern parts of the study area.

Despite these observations, significant relationships between rainfall indices and maize yields are spatially limited, affecting at most four out of ten divisions (e.g., for R1mm, Fig. 4g) and as few as one division (e.g., for SOS and R30mm, Fig. 4a and m). Additionally, divisions in the central part of the study area show no significant relationships, suggesting that maize in these divisions is less sensitive to rainfall variability.

In contrast to maize, cotton yields exhibit a strong negative correlation with indices reflecting wet conditions. Increases in interannual indices such as EOS, SL, R1mm, PRCPSEAS, R20mm, and R30mm are associated with reduced interannual yields in several sectors. However, RDD followed by SOS seems to increase interannual cotton yields in most of the region.

Overall, indices such as R1mm, PRCPSEAS, R20mm, and EOS negatively and significantly affect cotton yields in many sectors of the center part of the study area, where the adverse impact of wet conditions is more pronounced. However, few indices show a positive relationship with cotton yields. For example, the interannual RDD (Fig. 4p) is positively correlated with interannual yields displaying all parts of the region. Similarly, the start of the rainy season (SOS) improves significantly yields in three sectors, including one in the north and two in the southeastern part of the study area.

Spatial disparities in the relationships between indices and yields are evident between maize and cotton. For maize, significant relationships are primarily concentrated in the northern and southeastern regions, while for cotton, they are more prominent in most regions. These differences reflect the contrasting adaptation of the two crops to climatic conditions: maize thrives under wetter conditions, whereas cotton exhibits a negative response to similar conditions.

4 Discussion

In Northern Cameroon, rainfall plays a key role in the variation of crop yields. This study examines relationships between rainfall indices and crop yields in the Cameroon's Sudano-Sahelian zone, an area heavily reliant on rainfed agriculture. The results present statistical relationships between seasonal rainfall indices and the yields of two major crops, maize and cotton, two species at the heart of the region's crop systems. While cotton is the principal cash crop (Missé 2019), maize is the principal food crop for both rural and urban populations (Nzossié et al. 2010). These two crops are frequently cultivated in rotation within the cotton-maize-groundnut cropping system (Missé 2019). This study highlights two key findings based on the two distinct analysis scales explored: temporal and spatial. Firstly, temporal aggregation (averaging rainfall indices and maize and cotton yields across the years) shows that both maize and cotton yields respond similarly to rainfall indices such as the end of season (EOS) and the cumulative dry spells 15 (CDS15). Secondly, spatial aggregation (averaging rainfall indices and crop yields by divisions for maize and by sectors for cotton) reveals that maize yields are positively correlated with rainfall indices indicating wet conditions, while an inverse correlation is observed for cotton yields.

4.1 Similar responses of maize and cotton yields to rainfall indices under Temporal aggregation

The study reveals significant relationships between two indices (EOS and CDS15) and maize and cotton yields. Lengthening the end of the rainy season is beneficial for yields of both crops, with the same correlation coefficient ($r=0.66$), while increasing the cumulative dry spells 15 (CDS15) is negative for yields. The fact that these two indices are correlated in the same direction with two different crops with different timescale (1999–2021 for maize and 1991–2010 for cotton) highlights the idea of their influence on cropping systems in Northern Cameroon. This also highlights a transversal influence of water availability on different crops, independently of their specific physiological characteristics. For maize, the negative correlation observed with the CDS15 is in line with the results of Epule et al. (2017) who demonstrated the vulnerability of maize to drought in northern Uganda. In fact, dry spells cause poor germination, increase the need for replanting, and lead to wilting and drying out of maize crops (Oruonye et al. 2016) all of which disrupt the growth cycle, reduce photosynthetic efficiency, and ultimately result in yield losses. The end of season has a favorable influence on both crop yields. A longer rainy season can extend the growing season for crops, giving them more time to reach all the phenological stages required for optimum development. Similar results for cotton were reported by Njouenwet et al. (2021a, b) in the same study area. These authors found a strong positive correlation between the retreat date of the rainy season and cotton yields, thus noting the importance of this variable for explaining crop yields in Northern Cameroon. The importance of the end date of the rainy season for cereal yields has also been demonstrated in Burkina Faso by Kaboré et al. (2023). They found a positive correlation between the end of the rainy season and maize and sorghum yields. Similar results for maize have been found by Mosunmola et al. (2020) in Nigeria, that noted a positive correlation between the cessation date and maize yield indicating that a late cessation value will possibly enhance more maize yield.

Temporal aggregation has highlighted relationships between rainfall indices and crop yields in the entire study area. However, while this approach is informative, it remains partial because it doesn't capture local specificities. Spatial analysis emerges as a necessary step to take account spatial variations in yields in relation to rainfall indices.

4.2 Contrasting yields responses to wetter conditions under Spatial analysis

4.2.1 Maize yields responses to rainfall indices

To visualize spatial relationships by division between rainfall indices and maize yields, a mapped analysis was used. This approach provides a spatial visualization of the relationships between indices and yields, identifying areas where these relationships are strong, weak or non-existent. It also makes it possible to quantify the number of divisions where these relationships are significant. Six indices characterizing wet conditions showed a positive correlation with maize yields in certain divisions. Among these indices, the rainy days (R1mm) had the most significant impact, showing a positive correlation with yields in 4 out of 10 divisions: three in the Far-North region (Mayo-Kani, Diamaré, Mayo-Tsanaga) and one in the North region (Faro). This was followed by the season length (SL) and seasonal rainfall amount (PRCPSEAS), which also demonstrated a positive influence in the same divisions, except for Mayo-Tsanaga. In contrast, the wet days 20 (R20mm) and wet days 30 (R30mm) indices were correlated in only two and one division(s), respectively. These relationships highlight the critical role of heavy rainfall in optimizing maize yields in rainfed agriculture like mentioned by Kaboré et al. (2023) that have found a positive correlation with maize yields and the rainy days, end date, season length in North central region of Burkina Faso with a Sudano-Sahelian climate.

In fact, an increase of rainy days and a high seasonal rainfall amount ensure an even distribution of water in the soil, allowing optimum absorption of nutrients and a reduction in water stress. This aligns with the general literature on rainfed agriculture, which establishes that an increase in precipitation is generally associated with improved yields. These findings are consistent with those of Adamgbe and Ujoh (2013) in Nigeria who demonstrated a positive correlation between the annual number of rainy days, annual rainfall amounts and maize yield in similar climate conditions. These authors found that among several rainfall indices such as the annual number of rainy days, the annual rainfall totals are the most important variables for the variation in maize yield in Gboko (Nigeria). This is in line with observations done by Mosunmola et al. (2020) in Nigeria that maize requires a considerable amount of moisture of about 500 to 900 mm of well distributed rain for optimal yield. Therefore, as rainfall amount and rainy days are higher across the entire study area, they facilitate moisture availability promoting growth and optimal maturation which invariably means better maize yield in Northern Cameroon.

But the correlations were significant in only a few divisions, which can be explained by local disparities in rainfall conditions and the spatial and temporal distribution of rainfall within divisions and across the rainy season. Indeed, divisions differ in their climatic realities, with some exhibiting more homogeneous rainfall distribution than others. This variability in rainfall patterns likely contributes, at least in part, to the spatial variations observed in the correlations.

4.2.2 Cotton yield responses to rainfall indices

The spatial relationships between rainfall indices and cotton yields were analyzed by averaging rainfall indices and cotton yields over the 1991–2010 period for 37 SODECOTON sectors. Using this approach, the most prominent indices, based on the number of sectors showing significant correlations (8–17 out of the 37 sectors), include the end of the season (EOS), rainy days (R1mm), seasonal rainfall amount (PRCPSEAS), wet days 20 (R20mm) and relative dry days (RDD). All these indices related to wet conditions, except the RDD, are negatively correlated with cotton yields. Notably, R1mm and the PRCPSEAS stand out as the most salient indices, showing a strong negative correlation in the southeastern and the central parts of the study area, particularly in sectors such as Touboro, Sorombéo, Madingring, Bidzar, Mokolo-Koza. At first sight, these results seem to contradict those reported in the scientific literature, which generally show that an increase in rainfall leads to an increase in yields in rainfed agriculture. However, cotton is highly sensitive to anoxic conditions, and excessive moisture can be particularly harmful. Prolonged periods of relative humidity exceeding 90% can disrupt fertilization and result in significant yield losses (CIRAD 2003). Sultan et al. (2009) reported contrasting results in the same cotton-growing zone, where annual rainfall amounts were positively correlated with cotton yields during the 1993–2003 period. Furthermore, our findings reveal that the onset of the rainy season exhibits a positive correlation with cotton yields in three sectors, suggesting that a later onset of rainfall may result in better yields in these sectors. This observation contrasts again with Sultan et al. (2009), who found a negative correlation between the timing of rainfall onset and cotton yields. These discrepancies may be attributed to differences in the periods analyzed, the evolving impacts of climate variability over time, or differences in the number of sectors within the two studies.

In addition, the negative correlation between rainfall indices indicating wet conditions and cotton yields may be explained geographically by flooding or waterlogging episodes in the cotton-growing zone, particularly in the Far North region. In this regard, Bouba et al. (2017) identified 30 communes that experienced at least one flooding episode between 1934 and 2011, a period that includes this study period. These historical events probably led to destruction of crops over several years, thus affecting cotton yields throughout the cotton-growing zone. In the Sudano-Sahelian of Cameroon, floods typically occur between late August and early September. By this time, maize sown in early June has usually reached maturity, allowing farmers to harvest early if necessary to mitigate losses. In contrast, cotton is in a critical growth stage, either flowering or forming bolls, making it particularly vulnerable. Excess water can cause flowers and bolls drop, ultimately reducing yields. Waterlogging can reduce cotton yield by negatively impacting the plant's physiological processes, particularly through a reduction in boll number (Bange et al. 2004). Waterlogging is characterized by soil saturation, which restricts oxygen supply to plant roots, thereby affecting their growth and development (Müller et al. 2023). When the soil becomes saturated, the lack of oxygen in the root zone inhibits nutrient uptake and disrupts photosynthesis, leading to poor formation and fewer bolls. Few studies have been realized on the statistical link between rainfall indices and cotton yields in the same study area with the current study. For those that exist, there is a contradiction with the findings of this study. For instance, Njouenwet et al. (2021b) used rainfall data and cotton yields for sixteen years (2000–2015) at the level of SODECOTON regions to examine the link between rainfall indices and cotton yields in Northern Cameroon. In a spatial analysis, they found a strong positive correlation between several rainfall indices and cotton yields like the seasonal precipitation ($r=0{,}82$), the number of rainy days ($R=0{,}72$). These disparities may be attributed to differences on time and spatial scales used on these studies. A similar divergence arises with recent findings of Yaouba et al. (2024) that used rainfall data of the Garoua, Maroua and Ngaoundere weather stations and cotton yields at the scale of the hole Cameroon cotton-growing zone to establish a link between annual rainfall amount and cotton yields over a longer period (1974–2020). Their findings highlight a positive relative relationship between the annual rainfall amount and cotton yields. But the difference in the number of stations used in their study (3) compared to those used in this study (370), as well as the difference in the scale of the cotton yield data, could be sources of the divergence in results.

4.3 Limitations to the study

Nevertheless, the study has several limitations that need to be acknowledged. First, this work is based on the idea that rainfall is the sole factor explaining yield variability for the two crops. However, this approach has a significant limitation, as it does not consider other potentially influential variables, such as soil fertility, changes in technical practices, or farming methods, which could also contribute to these yield variations. But rainfall remains a critical factor in explaining yields in rainfed agriculture, which justifies its use in this study.

Furthermore, the NoCORA dataset from which the rainfall indices were calculated, does not fully cover the study area. In particular, the Logone-et-Chari division is almost entirely lacking rain gauges during the study period. This limitation could affect the accuracy of the precision of spatial interpolations. But the total number of rain gauges (370) used during the study period remains relatively high, and the inclusion of nearby stations, such as those in N'Djamena, could help mitigate this limitation. Additionally, rainfall indices were calculated for the full rainy season, whereas the growth and harvest periods of maize and cotton vary across regions. This temporal mismatch may introduce biases, particularly for weather events occurring outside the crops' active growth cycles. However, we do not have enough information about the seasonality of cultivated varieties to pin down for each sector or division the period inside which calculating the indices and thus preferred to perform a season-wide analysis rather than risking introducing biases related to bad knowledge of growth season.

Yields data also have limitations. Missing data for maize were relatively high in some divisions for the North region, potentially affecting the robustness of the findings. But these data encompass a sufficiently extensive temporal scale, allowing for an evaluation of long-term yields variations. In addition, the studied period is not the same for both crops although the overlap period is important: while maize yields cover the 1999–2021 period (23 years), cotton yields cover the 1991–2010 period (20 years). Besides, the spatial scales of analysis differ for the two crops: maize yield data is available at the divisional level, while cotton data is at the level of the SODECOTON sectors. Despite their differences, the studied areas — divisions for maize and sectors for cotton — generally cover the same geographical region, namely the Cameroon Sudano-Sahelian zone. Furthermore, these areas are of a similar magnitude and therefore can be compared.

Although the spatial and temporal aggregation of yield data helps to reduce noise and improve the robustness of the statistical analysis, it inevitably masks important local variability. Such aggregation may obscure localized responses to climatic factors, which could provide critical insights into micro-regional differences in crop sensitivity and adaptation. Consequently, the findings presented here should be interpreted with caution, recognizing that more detailed, site-specific analyses might reveal additional patterns that are not captured at the aggregated scale.

5 Conclusion

In a region where rainfed agriculture remains the backbone of livelihoods and the local economy, understanding the relationship between rainfall variability and crop production is essential. This study addressed statistical relationships between rainfall indices and maize (1999–2021) and cotton yields (1991–2010) in northern Cameroon using two complementary approaches: temporal and spatial aggregation. These analyses revealed nuanced crop responses, with maize yields positively correlated to rainfall indices indicating wet conditions– such as the rainy days (R1mm), the seasonal precipitation amount (PRCPSEAS), the rainy season length (SL)– while cotton yields tended to decline under similar conditions.

These findings underscore the differentiated water needs of maize and cotton, reinforcing the need for crop-specific adaptation strategies in response to rainfall variability. Despite using datasets with different temporal scales for maize and cotton, the convergence in rainfall indices-yields relationships for both crops confirms the central role of rainfall in shaping cropping outcomes. Furthermore, this study highlights the value of integrating analyses at different spatial and temporal scales to address data constraints and to develop a nuanced understanding of the relationships between rainfall variability and crop production.

These insights have implications for crop practices, adaptation planning, and public policy. For farmers, the differentiated water needs of maize and cotton highlight the importance of crop-specific strategies, including the selection of suitable varieties, the adjustment of planting calendars, and improved water management. Policymakers could invest in localized agro-climatic forecasting systems and improve the integration of climate data into agricultural advisory services. Looking ahead, given the central role of agriculture in Northern Cameroon, future research could build on these findings by integrating more spatially detailed analyses and incorporating temperature, soil proprieties variables to better capture local vulnerabilities of crop production and adaptive capacities of farmers. In parallel, agro-climatic forecasting—grounded in retrospective trends and defined climate scenarios—could help estimate future yield potential under different conditions. Together, these efforts would strengthen the development of decision-support tools and evidence-based interventions that guide sustainable and locally adapted strategies in the face of ongoing climatic changes.

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Declarations

Competing interests The authors declare no competing interests.

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