Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Projected Agroclimatic Changes and the Vulnerability of Rain-fed Cereal Systems in North-eastern Senegal

Awa Amadou SALL

awaamadousall@gmail.com

Alioune Diop University, Higher Institute of Agricultural and Rural Training, Biodiversity- Natural Resource Management-Climate Change Research Team (BIOGERENAT)

Elhadji FAYE

Alioune Diop University, Higher Institute of Agricultural and Rural Training, Biodiversity- Natural Resource Management-Climate Change Research Team (BIOGERENAT)

Cheikh Anta Diop

University of Dakar, DAKAR

Mehdi SAQALLI

Research House of Jean Jaurès University

Research Article

Keywords: climate change, agroclimatology, millet, sorghum, vulnerability, north-east Senegal

Posted Date: November 6th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11388566/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

In the Sahel region, rain-fed cereal production remains heavily dependent on climatic conditions, the future evolution of which raises major challenges for food security. This study assesses projected changes in agroclimatic conditions and the vulnerability of millet and sorghum cropping systems in five departments in north-eastern Senegal by 2050. Projections from a set of two CMIP6 models (CNRM-CM6-1 and MPI-ESM1-2-HR), calibrated using the Quantile Delta Mapping (QDM) method, were utilised under the SSP2-4.5 and SSP5-8.5 scenarios and compared with the 1981–2010 reference period. Agroclimatic indicators were calculated using CHIRPS and ERA5-Land data, and then correlated with departmental yields observed over the period 1981–2022. The results show a decrease in cumulative rainfall across all departments, reaching 17% in Podor under the SSP5-8.5 scenario, associated with a later onset and a shortening of the rainy season by 12 to 21 days. The projected warming, ranging from + 1.25°C to + 1.45°C depending on the scenario, is primarily reflected in an intensification of chronic heat stress linked to the mean temperature. The sensitivity analysis reveals that cumulative rainfall significantly explains yield variability in Kanel and Ranérou, but not in Podor, Matam and Linguère. A composite vulnerability index, combining exposure and agroclimatic sensitivity, identifies Podor as the most vulnerable department. These results highlight the need for region-specific adaptation strategies, based on agroclimatic indicators rather than on annual totals alone.

Introduction

West Africa, and in particular the Sahel region, is considered to be one of the most vulnerable regions to climate change due to the high interannual variability in rainfall, dependence on rain-fed agriculture and limited local adaptive capacity (Niang et al., 2014; Sultan and Gaetani, 2016; Dosio et al., 2020). In Senegal, rain-fed crops such as millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*), together with rice, form the basis of food security for a large proportion of the rural population, particularly in the northern and eastern parts of the country, where agroclimatic conditions are most challenging (Niang et al., 2014). However, the sensitivity of these crops to water and temperature fluctuations makes their yields particularly vulnerable to the effects of global warming (Lobell et al., 2011; Sultan et al., 2019).

Over recent decades, numerous studies have documented rainfall variability in the Sahel and its impacts on agricultural systems. Following the prolonged droughts of the 1970s-1990s, several studies have highlighted a recent trend towards partial re-humidification of the Sahel, attributed to the intensification of the West African monsoon and a northward shift of the intertropical convergence zone (Diallo et al., 2016; Panthou et al., 2018; Biasutti, 2019). However, there is no consensus on this trend at the sub-regional level, as projections remain mixed depending on the models and areas considered, particularly in the western fringe of the Sahel (Sylla et al., 2016). It is also accompanied by an increase in intra- and inter-annual variability, which complicates agricultural planning. In this context, climate projections from the sixth round of the *Coupled Model Intercomparison Project* (CMIP6) predict differing trends in rainfall and temperatures, depending on the emission pathways (SSP2-4.5, SSP5-8.5), heightening uncertainty regarding future agricultural yields (Eyring et al., 2016; Almazroui et al., 2020). The expected impacts on

rain-fed cereals also vary by region: whilst an increase in sorghum and maize yields is projected in the semi-arid zone of southern Burkina Faso and northern Ghana (Schultze et al., 2024), a negative impact on millet and sorghum is observed across West Africa under the SSP5-8.5 scenario (Sultan et al., 2023).

Whilst the impacts of climate change on West African rain-fed cereals have been the subject of numerous studies, these have mainly focused on regional or national scales, which obscure the heterogeneity of local conditions. However, Sahelian cropping systems are situated within marked bioclimatic gradients, where a distance of just a few dozen kilometres is sufficient to substantially alter production conditions. Furthermore, vulnerability mapping studies in West Africa show that the most exposed areas are concentrated immediately north of the 500 mm isohyet, which marks the northern limit of rain-fed agriculture (De Sherbinin et al., 2015). Furthermore, existing assessments are frequently based solely on annual rainfall totals, whilst actual agronomic constraints also depend on the seasonal timing, the intra-seasonal distribution of rainfall and temperature patterns. Finally, few studies explicitly link climate projections with analyses of observed yields at an administrative scale that would enable the guidance of public policy.

Beyond the average trends in climate parameters, assessing agricultural challenges requires linking the exposure of regions to projected changes with the specific sensitivity of cropping systems, two constituent dimensions of climate vulnerability as defined by the IPCC's conceptual framework (GIEC, 2014). This approach, widely used for the spatial prioritisation of adaptation actions at the sub-national level (Parker et al., 2019), has recently been applied in Senegal, where an assessment of the vulnerability of several crops has helped to identify the most exposed regions and opportunities for adaptation (Nguru and Mwongera, 2022). However, it remains under-utilised for rain-fed cereals in the north of the country, even though yield responses to climatic conditions there are spatially heterogeneous and annual rainfall totals only partially reflect the constraints to which crops are actually exposed.

In this regard, north-eastern Senegal constitutes a relevant case study. This region, which experiences the most challenging agroclimatic conditions in the country, spans a marked rainfall gradient, with average annual rainfall ranging from approximately 270 mm in Podor to nearly 490 mm in Kanel. It therefore offers, within a limited area, a diversity of conditions that allow for the analysis of the spatial variation in agroclimatic vulnerability. By utilising CMIP6 projections corrected for systematic biases, agroclimatic indicators derived from satellite data and reanalyses, as well as departmental time series of observed yields, this study aims to characterise the vulnerability of rain-fed cereal systems by 2050. More specifically, it seeks to (i) analyse the projected changes in key climatic and agroclimatic parameters (cumulative rainfall, seasonal timing, thermal constraints), (ii) assess the compatibility between future water and thermal conditions and the requirements of the growth cycles of millet and sorghum, and (iii) analyse the sensitivity of observed yields to climatic variables in order to construct a spatialised vulnerability index under the SSP2-4.5 and SSP5-8.5 scenarios.

This research contributes to our understanding of regional agroclimatic dynamics in the context of global change, whilst providing diagnostic insights useful for formulating differentiated adaptation

strategies for rain-fed production systems in the Sahel.

1 Data and methods

1.1 Study area

The study area covers north-eastern Senegal and includes the departments of Podor, Matam, Linguère, Ranérou and Kanel, extending between 14°30'N-16°30'N and 13°30'W-15°30'W, along the southern bank of the River Senegal, on the border with Mauritania (Fig. 1). This Sahelian region, covering an area of 56,920 km², is characterised by a semi-arid climate with a short rainy season (June-October). Annual rainfall varies from 200 to 600 mm along a north-south gradient, whilst maximum temperatures frequently exceed 40°C during the dry season (Sall et al., 2025).

From a socio-economic perspective, agriculture is the backbone of the regional economy and the primary source of employment and income for the majority of rural households. Millet accounts for the largest share of the cultivated area, particularly in Linguère and Ranérou, whereas sorghum dominates in Podor, Matam and Kanel, and maize remains marginal. Podor, Matam and Kanel combine rain-fed agriculture with flood-recession crops and irrigated areas along the river, whereas Linguère and Ranérou rely exclusively on rain-fed agriculture. This study focuses solely on rain-fed cereal farming systems, as these are the only ones directly dependent on the variability and changes in seasonal climatic conditions. A fuller description of the agricultural context and production systems is given in Online Resource 1 (Text S1).

1.2 Climate data

Daily rainfall for 1981–2024 was obtained from the CHIRPS Daily product (approximately 5 km; Funk et al., 2015) via Google Earth Engine, and daily maximum and minimum temperatures from the ERA5-Land reanalysis (approximately 9 km; Hersbach et al., 2020); both were aggregated to departmental level by averaging the pixels within each administrative boundary. Climate projections for 2025–2050 under SSP2-4.5 and SSP5-8.5 were drawn from the NASA NEX-GDDP-CMIP6 collection (approximately 25 km) for two models, CNRM-CM6-1 and MPI-ESM1-2-HR, selected for their performance over West Africa (Almazroui et al., 2020; Dosio et al., 2020; Taguela et al., 2025). The daily series were bias-corrected by Quantile Delta Mapping against CHIRPS and ERA5-Land over the 1981–2010 reference period (Cannon et al., 2015), and a two-model ensemble mean was used for all analyses. The datasets, model selection and bias-correction procedure, together with the values for each model, are detailed in Online Resource 1 (Text S1-S2 and Tables S1-S2).

1.3 Agronomic data

Agricultural data from the DAPSA (Directorate for Agricultural Analysis, Forecasting and Statistics) are available at the departmental level for the period 1981–2022 in Podor, Matam and Linguère, and for 2002–2022 in Kanel and Ranérou (the latter two departments having only acquired this status in 2002). For sorghum, the time series begin in 1982 in Matam and Podor and in 1995 in Linguère. These yield

series relate exclusively to areas under rain-fed cultivation, excluding floodplain crops and irrigated areas. This restriction ensures that the variability analysed accurately reflects the response of cropping systems to seasonal climatic conditions, rather than that of systems benefiting from supplementary water supplies.

The characteristics of the cultivated varieties (growth cycles, water requirements) were extracted from a literature review based on variety data sheets (Cissé, 2015; Sy, 2011) and specialist publications (Upadhyaya et al., 2008; Kholavà et al., 2010; Chantereau et al., 2013; Théra, 2017; Debieu et al., 2018; Kadri et al., 2019; Diatta et al., 2020; Gano et al., 2021). The data are summarised in Tables 1 and 2. For growth cycles expressed as ranges, the maximum value was used to ensure a conservative estimate.

Table 1
Agronomic characteristics of the main varieties of millet and sorghum grown in northeastern Senegal

Species	**Millet**			**Sorghum**				
	Souna 3	**ICTP 8203**	**GB 8735**	**Gawane**	**Chakti**	**CE 180 – 33**	**Payenne**	**Golobé**
Date of introduction	1969	1982	1987	2006	2016	1983	2015	2015
Cycle length (days)	85–90	70	80	85	63	90	85–90	87–90
Water requirement (mm)	420	350–450	350–600	300–400	300–550	400–700	400–500	400–500

Table 2
Water and temperature requirements of millet and sorghum in rainfed cultivation

Species	Parameter	Degree of constraint			
		None	Low	Medium	Severe
Millet	P an. (mm)	> 350	[350 – 300]	]300 – 200]	< 200 and > 1000
	Average daily temperature	[22–28]	]28–32]	]32–35	> 35
	Max. daytime temperature	< 38	[38–40]	]40–45]	> 45
	Min. daytime temperature	[20 – 18]	]18 – 17]	]17 – 15]	< 15
Sorghum	P an. (mm)	> 400	[400 – 350]	]350 – 300]	< 300
	Average daily temperature	[22–28]	]28–32]	]32–35	> 35
	Max. daytime temperature	< 38	[38–40]	]40–45]	> 45
	Min. daytime temperature	[20 – 18]	]18 – 17]	]17 – 15]	< 15

1.4 Methodology

1.4.1 Precipitation and agroclimatic indicators

The precipitation and agroclimatic indicators were calculated using historical daily precipitation time series (CHIRPS, 1981–2010) and projected (CNRM–CM6–1 + MPI–ESM1–2–HR ensemble, 2025–2050) precipitation data for the SSP2-4.5 and SSP5-8.5 scenarios, across the five departments of north-eastern Senegal.

Annual rainfall totals were obtained by summing the daily rainfall values. Inter-annual averages were calculated for each period and scenario, enabling the quantification of absolute and relative deviations from the 1981–2010 reference period.

The rainy season was characterised by its timing, the number of rainy days and intra-seasonal dry spells. The start of the season corresponds to the first day, from May 1st onwards, on which a cumulative total of at least 20 mm is reached over three consecutive days, with no dry spell lasting more than 7 days in the following 30 days (Guèye and Sivakumar, 1992). The end of the season was estimated using a simplified water balance from September 15th, with an initial usable water reserve of 60 mm and a daily evapotranspiration rate of 5 mm, in accordance with FAO values for this region (Allan et al., 1998). The end date corresponds to the first day on which the water reserve reaches zero after accounting for daily rainfall.

The duration of the rainy season was calculated as the number of days between the start and the end of the season. A rainy day is defined as one with rainfall of ≥ 1 mm. Intra-seasonal variability was characterised by the maximum number of consecutive dry days (CDD, threshold < 1 mm) and by the frequency of dry spells lasting more than 7 days, calculated exclusively during the rainy season. Anomalies in the start, end and duration of the season were expressed in days relative to the historical period.

1.4.2 Agroclimatic impacts on rain-fed cereal crops

The agroclimatic impacts on millet and sorghum were assessed using three indicators calculated for each variety, department and scenario: phenological suitability, minimum water requirement and overall agro-hydrological suitability.

Phenological suitability corresponds to the percentage of years in which the duration of the rainy season is sufficient to cover the variety's complete life cycle. Minimum water sufficiency corresponds to the percentage of years in which the cumulative annual rainfall meets the variety's minimum water requirement, as defined in Table 1. Overall agro-hydrological suitability combines these two dimensions: a year is considered favourable when the rainy season covers both the variety's life cycle and its minimum water requirement.

These indicators were calculated for the historical period (1981–2010) and for the projections (2025–2050) under SSP2-4.5 and SSP5-8.5, using CHIRPS data for the historical period and the corrected CNRM-CM6-1 + MPI-ESM1-2-HR data set for the projections. The results are presented as scatter plots

for phenological suitability and as heat maps for water satisfaction and overall agro-hydrological suitability.

1.4.3 Analysis of temperatures and thermal constraints

Daily maximum and minimum temperatures were extracted from the ERA5-Land reanalysis for the historical period (1981–2010) and from the corrected CNRM-CM6-1 + MPI-ESM1-2-HR ensemble for the projection period (2025–2050) under the SSP2-4.5 and SSP5-8 scenarios. The daily mean temperature was calculated as the arithmetic mean of the maximum and minimum temperatures.

Temperature anomalies were defined as the difference between the interannual mean of projected temperatures (2025–2050) and the historical mean (1981–2010), for each department, scenario and variable (Tmax, Tmin, Tmoy).

Thermal stresses were analysed exclusively during the seasonal window defined by the start and end dates of the rainy season. Only maximum (Tmax) and average (Tmoy) temperatures were considered, as minimum temperatures consistently remained above the critical threshold of 15°C during the rainy season in the study area. The stress thresholds are presented in Table 2. For each year, the number of days falling within each stress level was calculated over the seasonal window, then converted into a percentage of the total number of days in the season. Interannual averages of stress frequencies were calculated for each department and scenario. Only the low, medium and severe stress levels were plotted graphically.

1.4.4 Analysis of climate-yield relationships

Interannual yield trends were analysed over the available period for each department. Yield anomalies were calculated as the difference between the annual yield and the average for the reference period, and compared with annual rainfall anomalies calculated in a similar manner, in order to assess the relationship between rainfall variability and yield variability. To ensure comparability, the anomalies were plotted over a common baseline period specific to each department and each crop.

The sensitivity of yields to climatic conditions was assessed using Pearson's correlation coefficient, calculated separately for each department and each crop between annual yields and seven climatic indicators: cumulative rainfall, the duration of the rainy season, the maximum number of consecutive dry days, and the frequencies of days with low and medium thermal stress based on Tmax (38–40°C and 40–45°C) and Tmoy (28–32°C and 32–35°C). Statistical significance was assessed at the 5% level, and 95% confidence intervals were estimated for each coefficient. The results were summarised in the form of a correlation matrix.

A composite climate vulnerability index was constructed for each department under the SSP2-4.5 and SSP5-8.5 scenarios by 2050. This index combines two equally weighted dimensions: exposure to climate change (50%) and the agroclimatic sensitivity of cropping systems (50%). The exposure dimension comprises five components: projected rainfall deficit, shortening of the rainy season, projected number

of consecutive dry days, and projected increases in the frequency of thermal stress on Tmax and Tmoy. The sensitivity dimension comprises three components derived from historical conditions: deficits in meeting the minimum water requirements of millet and sorghum, and the historical frequency of thermal stress on Tmoy. Thermal stress on the mean temperature features in both dimensions from complementary perspectives: exposure measures its projected intensification, whilst sensitivity reflects the level of pre-existing structural thermal stress, as a system already under severe stress during the historical period is more vulnerable to any future worsening.

Adaptive capacity, the third component of the conceptual framework for vulnerability (GIEC, 2014), has not been incorporated into the index. The indicators that characterise it (access to improved seeds, level of equipment, use of inputs, access to credit and agricultural extension services) are not available on an annual basis or at the departmental level for the period under study. The proposed index therefore constitutes a measure of the biophysical vulnerability of rain-fed cereal systems, rather than an integrated assessment of their socio-economic vulnerability.

Each component was standardised on a scale of 0 to 100 using the min-max method, after which the composite index was classified into four levels: low (< 25), moderate (25–50), high (50–75) and very high (≥ 75). The results were spatialised in the form of departmental choropleth maps. The sensitivity of the index to the choice of weightings was assessed by recalculating the scores using several alternative schemes (see the results section).

All analyses were carried out in R (v4.5) using the dplyr, lubridate, sf, ggplot2 and patchwork packages.

2 Results

2.1 Projected changes in climatic and agroclimatic parameters

2.1.1 Annual rainfall totals

Projected annual rainfall totals are set to decrease across all departments compared with the historical reference period (1981–2010), regardless of the scenario considered. This decline is more pronounced under SSP5-8.5 than under SSP2-4.5 (Online Resource 1, Table S1), indicating a greater rainfall deficit as radiative forcing intensifies.

Under the SSP2-4.5 scenario, the decreases remain moderate and relatively consistent across departments, with variations ranging from − 24.2 mm in Matam to -34.5 mm in Linguère. Under the SSP5-8.5 scenario, the deficits become more pronounced in all departments. The sharpest reductions are observed in Linguère (-60.8 mm) and in Podor and Kanel (-46.6 mm). In relative terms, Podor shows the greatest decrease under the SSP5-8.5 scenario, confirming its greater vulnerability to water scarcity (Fig. 2).

2.1.2 Seasonal calendar and rainy season

Analysis of the seasonal calendar shows a later start to the rainy season across all departments under both scenarios, with positive anomalies ranging from + 11 to + 21 days depending on the department and the scenario (table 4). The delay is more pronounced under SSP5-8.5 in most cases, particularly in Linguère and Podor, whilst Matam shows the smallest shifts. The end date of the season hardly varies compared with the historical period, with small anomalies close to zero in most departments (Fig. 3; Online Resource 1, Fig. S1 and Table S3).

Consequently, the duration of the rainy season is shortening in all departments. The reductions range from – 12 days in Matam to -21 days in Linguère under SSP5-8.5, with equally marked decreases in Kanel, Podor and Ranérou. The shortening is generally more pronounced under SSP5-8.5 than under SSP2-4.5, except in Kanel and Matam, where the two scenarios yield the same values (Fig. 3; Online Resource 1, Fig. S1 and Table S3).

At the same time, the number of rainy days is increasing in all departments. Positive anomalies range from + 2 days in Podor under SSP5-8.5 to + 10 days in Ranérou under SSP2-4.5. Ranérou records the largest increases, followed by Kanel and Matam, whilst Podor and Linguère show the smallest increases (Online Resource 1, Fig. S1 and Table S3).

2.1.3 Intra-seasonal dry spells

The maximum number of consecutive dry days is decreasing in all departments under both scenarios, with negative anomalies ranging from – 1.3 to -2.4 days (Online Resource 1, Fig. S2). Podor shows the greatest reduction under SSP2-4.5, whilst Matam and Ranérou show the smallest decreases. Similarly, the frequency of dry spells lasting more than 7 days decreases across all departments, with a particularly marked reduction in Podor. In all cases, the decreases are generally greater under SSP2-4.5 than under SSP5-8.5.

2.1.4 Projected temperature trends

Average temperature anomalies, resulting from the combination of maximum and minimum temperatures, range from + 1.21°C in Podor to + 1.27°C in Matam under SSP2-4.5, and from + 1.39°C in Linguère and Podor to + 1.48°C in Matam and Kanel under SSP5-8.5. The average increase across the entire study area is estimated at + 1.25°C under SSP2-4.5 and + 1.45°C under SSP5-8.5, reflecting moderate but significant warming by 2050. Maximum- and minimum-temperature anomalies by department are given in Online Resource 1 (Text S3, Fig. S3 and Table S2).

2.2 Agroclimatic impacts on rain-fed cereal crops

The match between the duration of the rainy season and variety growth cycles decreases across all departments under the projected scenarios, with a more marked deterioration under SSP5-8.5. The

satisfaction of the minimum water requirement deteriorates similarly across all departments. Detailed results for both indicators are given in Online Resource 1 (Text S4-S5 and Figs. S4-S5).

2.2.1 Overall agro-hydrological suitability

The overall hydro-climatic suitability indicator, which combines cycle coverage and water requirement fulfilment, confirms a generalised deterioration. For millet, over the historical period, Kanel shows the highest rates, with values reaching 93% for Chakti, 87% for ICTP 8203 and 83% for GB 8735. Ranérou shows satisfactory historical rates for short-cycle varieties (83% for Chakti and ICTP 8203) but lower rates for long-cycle varieties such as Souna 3 (43%). Linguère has moderate historical rates, ranging from 10% for Souna 3 to 80% for Chakti. Matam and Podor have very low historical rates, not exceeding 48% and 33% respectively for Chakti, the most favourable variety. Under SSP2-4.5, the rates decrease in all departments; under SSP5-8.5, they fall to 0% for most varieties in Linguère, Matam and Podor, and decline sharply in Kanel, particularly for long-cycle varieties such as Souna 3 (15%) and Gawane (27%) (Fig. 4).

For sorghum, the overall agro-hydric suitability rates are lower than for millet in all departments and scenarios. Historically, Kanel recorded rates of 60% for all varieties and Ranérou 50%. The other departments show very low rates, below 10% in Linguère and Matam and 4% in Podor. Under SSP2-4.5, the rates fall to 35% in Kanel and 23% in Ranérou, whilst Linguère, Matam and Podor record rates of zero or near zero. Under SSP5-8.5, the decline intensifies, with rates falling to 15% in Kanel, 8% in Ranérou and 0% in the other three departments for all sorghum varieties (Fig. 4).

2.3 Thermal stresses on crops during the rainy season

Thermal stress based on maximum temperature remains generally moderate during the rainy season. Under SSP5-8.5 it intensifies in all departments, reaching 18.6% of rainy-season days in Podor and 14.5% in Matam, whilst Linguère, Kanel and Ranérou remain below 4%; no severe stress (Tmax > 45°C) occurs under either scenario (Online Resource 1, Text S6 and Fig. S6).

Constraints related to average temperatures are much more pronounced. Over the historical period, almost all days during the rainy season exhibited at least one low-level constraint (Tmoy ≥ 28°C) in all departments, with total frequencies ranging from 70.4 to 83.1%. Mild stress predominates by a wide margin, whilst moderate stress (32–35°C) ranges from 3.0% in Linguère to 23.3% in Matam and 20.0% in Podor. Under SSP2-4.5, the moderate stress increases significantly in Matam (+ 9.4 points, rising from 23.3% to 32.7%) and Podor (+ 16.2 points, from 20.0% to 36.2%). Kanel, Ranerou and Linguère show a slight decrease in average stress (-1.9, -1.5 and − 0.2 percentage points respectively). Under SSP5-8.5, the trend towards greater stress continues: the average stress exceeds 36% in Matam and 40% in Podor. Kanel, Linguère and Ranérou also reach total frequencies close to 100%, but low stress levels predominate by a wide margin (Fig. 5).

Stress related to maximum temperatures remains limited during the rainy season, with no severe episodes, whilst stress related to average temperatures is virtually constant and intensifies under the projected scenarios. The thermal risk for millet and sorghum in north-eastern Senegal therefore appears to be more closely linked to chronic thermal stress due to average temperatures than to peaks of extreme heat due to maximum temperatures.

2.4 Climate-Yield Relationships

2.4.1 Trends and Interannual Variability in Yields

Yield anomalies for millet and sorghum over the period 1981–2022 show marked interannual variability and contrasting patterns across departments, with a clear visual correspondence between positive rainfall and yield anomalies in Kanel and Ranérou that is weaker in Podor and Matam and absent in Linguère (Online Resource 1, Text S7 and Fig. S7).

2.4.2 Sensitivity of yields to climate indicators

Analysis of the correlations between cereal yields and the seven selected climate indicators reveals a clear spatial pattern, characterised by a contrast between the departments of north-eastern Senegal (Fig. 6).

Annual cumulative rainfall is the only indicator to show significant positive correlations for both crops simultaneously and in the same two departments. In Ranérou, the coefficients reach + 0.63 for millet and + 0.50 for sorghum; in Kanel, they stand at + 0.46 and + 0.47 respectively. In Podor, Matam and Linguère, the correlations with cumulative rainfall remain weak and non-significant, ranging from − 0.28 to + 0.10.

The duration of the rainy season yields only two significant correlations, which are opposite in direction. In Matam, it is positively correlated with millet yields (r = + 0.33). In Podor, it is negatively correlated with sorghum yields (r = -0.39).

The maximum number of consecutive dry days shows no significant correlation with yields, regardless of the department or crop considered, with the coefficients ranging from − 0.04 to + 0.29.

Thermal stress yields five significant correlations, all of which are found in Linguère and Podor and are predominantly positive (Online Resource 1, Text S8).

Finally, the interpretation of statistical significance must take into account the heterogeneity in sample sizes across departments. Kanel and Ranérou have only around twenty observations, compared with around forty in Podor, Matam and Linguère. This difference explains why certain coefficients with high absolute values, such as the correlation between low thermal stress on maximum temperature and millet yields in Kanel (r = -0.55) or between low thermal stress on mean temperature and sorghum yields in Ranérou (r = + 0.58), do not reach the significance threshold.

2.4.3 Projected agroclimatic vulnerability (2025–2050)

Mapping of the composite vulnerability index reveals spatial differences between the departments in the study area depending on the climate scenario considered (Fig. 7). Under the SSP2-4.5 scenario, Podor falls into the high vulnerability class, Matam and Kanel into the moderate class, whilst Linguère and Ranérou fall into the low class. Under the SSP5-8.5 scenario, Podor moves into the very high class, Linguère moves from the low class to the moderate class, whilst Ranérou remains in the low class and Matam and Kanel retain their moderate level of vulnerability.

The robustness of the ranking to the choice of weightings was verified by recalculating the index under three alternative weighting schemes (equal weights across the eight components, 70% weight on exposure, and 70% weight on sensitivity). Podor remained the most vulnerable department and no department changed vulnerability class, so the spatial hierarchy does not depend on the specific choice of weightings (Online Resource 1, Text S9).

The increase in vulnerability between the two scenarios mainly affects Podor, which moves from the ‘high’ class to the ‘very high’ class, and, to a lesser extent, Linguère, which moves from ‘low’ to ‘moderate’. The other departments retain their vulnerability levels, reflecting a relative stability in the spatial hierarchy from one scenario to the next. This differentiation - whereby the most exposed departments do not necessarily coincide with those whose yields are most sensitive to rainfall - is examined in the discussion.

3 Discussion

Climate projections for 2050 in north-eastern Senegal indicate a decrease in annual cumulative rainfall across all departments, which is more pronounced under the SSP5-8.5 scenario, where the deficit reaches – 17% in Podor. This decrease is consistent across the two models used (CNRM-CM6-1 and MPI-ESM1-2-HR), which both predict a decline in all departments under the SSP5-8.5 scenario and in the majority of them under the SSP2-4.5 scenario. This convergence between models reinforces the consistency of the drying trend, in a context where Sahelian rainfall projections remain characterised by high inter-model uncertainty (Sylla et al., 2016). Nevertheless, it places our results at odds with some of the recent CMIP6 literature, which, by contrast, projects an intensification of the West African monsoon and increased rainfall over the Sahel (Monerie et al., 2020; Bobde et al., 2024; Diouf et al., 2025).

Beyond changes in cumulative rainfall, our results show, above all, an unfavourable reorganisation of the seasonal timeline. These developments thus further jeopardise the completion of the growing cycles of late-maturing varieties and increase the risk of terminal water stress, which is already common in the region (Sultan et al., 2023).

The projected reduction in intra-seasonal dry spells is certainly a partially favourable sign, but it is not sufficient to offset the overall shortening of the growing season. Recent research carried out in Senegal shows that the choice of sowing window interacts with the type of variety: dry sowing, traditionally practised by farmers, yields an 8–12% increase in yield for improved local varieties, whilst dual-purpose varieties benefit more from sowing timed to coincide with the onset of the rains (Akinseye et al., 2024).

However, these constraints linked to the rainfall regime do not operate in isolation. In addition to this water stress, there is widespread and spatially homogeneous warming, of the order of + 1.25°C under SSP2-4.5 and + 1.45°C under SSP5-8.5. Our results reveal that the thermal risk to crops is more closely associated with chronic stress linked to average temperature than with episodes of extreme heat characterised by maximum temperature.

This distinction is important for interpreting agricultural impacts, as prolonged exposure to high temperatures-even moderate ones-can shorten the flowering and ripening phases of millet (Mohamed et al., 2025)and affect its reproductive fertility (Schlenker and Lobell, 2010). The combination of a rainfall deficit and chronic heat stress thus constitutes a particularly adverse agroclimatic constraint: both factors act in the same way on crop performance and cannot be considered independently (Sultan and Gaetani, 2016).

A comparison with recent literature also highlights significant uncertainty regarding certain thermal and rainfall indicators. Whilst our projections indicate a decrease in the number of consecutive dry days, several studies based on CORDEX regional models, on the contrary, project an increase in the probability of prolonged dry spells (≥ 7 and 10 days) in the western Sahel, as well as a delay in the start of the growing season of up to two weeks by the end of the century (Wainwright et al., 2021; Basse et al., 2024). Similarly, the projected increase in interannual variability of Sahelian rainfall, with a higher frequency of extreme wet and dry seasons (Yang et al., 2025), serves as a reminder that changes in average rainfall totals alone are insufficient to characterise agricultural risk.

A sensitivity analysis of historical yields sheds light on how these climatic constraints translate into variability in production. It reveals a clear spatial pattern: annual cumulative rainfall is strongly and significantly correlated with millet and sorghum yields in Kanel and Ranérou, whilst no significant correlation is observed in Podor, Matam and Linguère. This finding is consistent with the conclusions of Sultan et al. (2013), according to which the sensitivity of millet and sorghum yields to rainfall varies according to regional climatic conditions, with water stress constituting a major limiting factor in Sahelian environments.

In Kanel and Ranérou, where historical annual rainfall totals are the highest in the study area, production occurs within a rainfall range where interannual variations in precipitation have a direct impact on yields, making the annual rainfall total an important determinant of their variability. In Podor and Matam, by contrast, rainfall totals are structurally low and water requirements are already critical in an average year.

Soil characteristics are an important influential factor in this regard. In Sahelian environments with sandy soils, which are prone to surface crusting and have inherently low fertility, yield variability can be modulated by the heterogeneity of soil properties, its infiltration capacity and its nutrient status; these may alternate with water availability as limiting factors depending on rainfall conditions (Rockström et al., 1999). Recent studies thus show that, on sandy soils with low organic matter content, the inter-annual stability of millet yields is closely linked to fertility management (Aboubacar et al., 2022), with

phosphorus potentially acting as a limiting factor when water is not the primary limiting factor (Buerkert et al., 2001).

Above all, the annual total partly masks the temporal distribution of rainfall. The start date of the growing season, its actual duration and the occurrence of prolonged dry spells during sensitive stages of the crop cycle strongly influence the productivity of millet and sorghum (Sivakumar, 1988; Marteau et al., 2010). False starts followed by early dry spells can lead to the death of young plants and necessitate replanting, whilst post-flowering dry spells compromise grain filling (Marteau et al., 2010). Porkka et al. (2021) also show that, across the Sahel, an increase in cumulative annual rainfall is only weakly, if at all, associated with an improvement in the intra-seasonal characteristics relevant to agriculture.

These constraints (hydrological, thermal, edaphic, biotic and intraseasonal) do not affect the five departments uniformly. Combining them into a composite vulnerability index enables the establishment of a spatial hierarchy of climate risk. Podor emerges as the most vulnerable department under both scenarios, combining the highest exposure (particularly marked rainfall deficit and shortening of the growing season) with high structural agroclimatic sensitivity, characterised in particular by water requirement satisfaction rates that are among the lowest in the area. Conversely, Kanel and Ranérou exhibit the lowest levels of vulnerability, consistent with their historically more favourable agroclimatic conditions.

This hierarchy highlights an important finding: the departments where yields are most closely dependent on rainfall are not necessarily the most vulnerable. The sensitivity of a yield to a climatic variable is therefore not necessarily the same as the overall vulnerability of the agricultural system, which depends on the combination of exposure, sensitivity and pre-existing structural constraints.

This hierarchy must, however, be interpreted in the context of the scope of the analysis. The proposed index characterises rain-fed cereal systems alone. The hierarchy established here should therefore be understood as relating specifically to rain-fed systems, and not as an assessment of the departments' overall food vulnerability. These results nevertheless argue in favour of a territorialised approach to adaptation, incorporating the diversity of local conditions, as recommended by Twumasi-Ankrah et al. (2025).

The scope of these results must, however, be assessed in light of several limitations. Firstly, the projections are based on two climate models, CNRM-CM6-1 and MPI-ESM1-2-HR. Although their convergence regarding the direction of rainfall trends reinforces the consistency of the signal obtained, a broader multi-model ensemble would be necessary to better characterise the magnitude of the changes and the uncertainty associated with extreme events. Secondly, the analysis of climate-yield relationships is based on statistical correlations and a vulnerability index, rather than on explicit biophysical modelling of crops. It therefore does not allow for the precise isolation of the effects of farming practices, fertilisation, soil degradation or genetic changes in crop varieties, which can significantly modulate the actual response in yields (Lobell, 2014).

Thirdly, the analysis relies primarily on rainfall and does not take into account certain water balance processes, such as runoff, actual evapotranspiration or soil water-holding capacity, which determine the actual availability of water for crops. Fourthly, the vulnerability index does not take into account the adaptive capacity of farms, due to a lack of socio-economic data available at departmental level and on an annual basis. However, available field surveys show that production conditions remain largely unmechanised and that the use of inputs remains limited and uneven across departments, suggesting that incorporating this dimension could alter the resulting vulnerability hierarchy. Finally, the heterogeneity in sample sizes across departments (around twenty years' worth of data in Kanel and Ranérou compared with around forty elsewhere) reduces the statistical power of the tests in the recently created departments and calls for caution when interpreting certain non-significant correlations.

Conclusion

This study assessed the projected changes in agroclimatic conditions and the vulnerability of rain-fed cereal systems in five departments in north-eastern Senegal by 2050, by combining adjusted climate projections, agroclimatic indicators and an analysis of observed yields over the period 1981–2022.

The results indicate an unfavourable trend in production conditions under both scenarios. Cumulative rainfall is decreasing across all departments, with a deficit reaching 17% in Podor under SSP5-8.5, accompanied by a later start and a shorter rainy season, which disrupt the alignment between the cropping window and the growth cycles of millet and sorghum. The projected warming is reflected less in episodes of extreme heat than in chronic heat stress linked to average temperature, which is particularly pronounced in Matam and Podor.

Analysis of observed yields reveals spatially differentiated climate sensitivity: annual cumulative rainfall is a significant determinant of yield variability in Kanel and Ranérou, but not in Podor, Matam and Linguère, where edaphic, biotic and intra-seasonal factors are likely to be at play. The composite vulnerability index establishes a spatial hierarchy of risk, with Podor ranking highest under both scenarios, due to high exposure combined with pre-existing structural fragility, whilst Kanel and Ranérou exhibit the lowest levels of vulnerability. This result highlights that the sensitivity of yields to a single climatic variable should not be conflated with the overall vulnerability of the agricultural system.

These conclusions call for locally tailored adaptation strategies: the introduction of short-cycle varieties and improved fertility management in Podor and Matam, where the constraint is structural; mitigating inter-annual variability through climate services and the adjustment of sowing schedules in Kanel and Ranérou. Better integration of the biophysical and socio-economic dimensions of vulnerability (combining crop modelling, soil characterisation and knowledge of farmers' practices) would be a crucial step towards translating these assessments into operational strategies.

Declarations

Ethical declarations

Not applicable.

Clinical trial number

Not applicable.

Funding

Not applicable.

Author Contribution

A.A.S. : Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing original draft.E.F., C.D., M.S. : Supervision, Writing, review and editing.

Data Availability

The climate datasets used in this study are publicly available: CHIRPS Daily (Climate Hazards Group, University of California Santa Barbara), accessed through Google Earth Engine; ERA5-Land (Copernicus Climate Change Service / ECMWF); and the NASA NEX-GDDP-CMIP6 downscaled projections (CNRM-CM6-1 and MPI-ESM1-2-HR). The departmental crop-yield data were provided by the Directorate for Agricultural Analysis, Forecasting and Statistics (DAPSA) of Senegal and are available from the corresponding author upon reasonable request, subject to DAPSA's permission. The bias-corrected datasets and the R scripts used for the analyses are available from the corresponding author upon reasonable request.

References

1. Aboubacar DKTI, Ali I, Fatondji D, Bado V, Ettien DJB (2022) *Pearl millet yields and yield stability under long-term soil fertility management in the Sahel*. https://doi.org/10.1002/agj2.21129
2. Akinseye FM, Zagre I, Faye A, Joseph JE, Worou ON et al (2024) Exploring adaptation strategies for smallholder farmers in dryland farming systems and impact on pearl millet production under climate change in West Africa. *Frontiers in Agronomy*, *6*. https://doi.org/10.3389/fagro.2024.1428630
3. Allan R, Pereira L, Smith M (1998) *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*

4. Almazroui M, Saeed F, Saeed S, Islam M, Ismail M et al (2020) Projected Change in Temperature and Precipitation Over Africa from CMIP6. Earth Syst Environ. *4*https://doi.org/10.1007/s41748-020-00161-x
5. Basse J, Camara M, Diba I, Diedhiou A (2024) Projected Changes in Dry and Wet Spells over West Africa during Monsoon Season Using Markov Chain Approach. Climate 12(12). https://doi.org/10.3390/cli12120211
6. Biasutti M (2019) Rainfall trends in the African Sahel: Characteristics, processes, and causes. WIREs Clim Change 10(4):22. https://doi.org/10.1002/wcc.591
7. Bobde V, Akinsanola AA, Folorunsho AH, Adebiyi AA, Adeyeri OE (2024) Projected regional changes in mean and extreme precipitation over Africa in CMIP6 models. Environ Res Lett 19(7). https://doi.org/10.1088/1748-9326/ad545c
8. Buerkert A, Bationo A, Piepho H-P (2001) *Efficient Phosphorus Application Strategies for Increased Crop Production in Sub- Saharan West Africa*. https://hub.ifdc.org/handle/20.500.14297/2885
9. Cannon AJ, Sobie SR, Murdock TQ (2015) *Bias Correction of GCM Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and Extremes?* https://doi.org/10.1175/JCLI-D-14-00754.1
10. Chantereau J, cruz JF, Ratnadass A, Trouche G, Fliedel G (2013) Sorgho. Editions Quae, CTA, Presses agronomiques de Gembloux
11. Cissé N (2015) Fiches variétales Niébé & Sorgho. Isra - Fiches techniques 4(4):14
12. De Sherbinin A, Chai-Onn T, Jaiteh M, Mara V, Pistolesi L et al (2015) Data Integration for Climate Vulnerability Mapping in West Africa. ISPRS Int J Geo-Information 4(4):2561–2582. https://doi.org/10.3390/ijgi4042561
13. Debieu M, Sine B, Passot S, Grondin A, Akata E et al (2018) Response to early drought stress and identification of QTLs controlling biomass production under drought in pearl millet. PLoS ONE 13(10). https://doi.org/10.1371/journal.pone.0201635
14. Diallo I, Giorgi F, Deme A, Tall M, Mariotti L et al (2016) Projected changes of summer monsoon extremes and hydroclimatic regimes over West Africa for the twenty-first century. Clim Dyn 47(12):3931–3954. https://doi.org/10.1007/s00382-016-3052-4
15. Diatta C, Ndiaye M, Diatta-Holgate E, Sarr MP, Kane R et al (2020) Guide des bonnes pratiques agricoles pour la culture du sorgho grain au Sénégal. ISRA Séries Fiches Techniques 55(2):26
16. Diouf I, Fall P, Diouf S, Diouf AK, Barry M et al (2025) *Assessment of Spatio-Temporal Trends in Rainfall Indices in Senegal: Validation of CMIP6 Models over the Historical Period and Projections Under Future Climate Scenarios*. 19. https://doi.org/10.20944/preprints202505.0347.v1
17. Dosio A, Turner AG, Tamoffo AT, Sylla MB, Lennard C et al (2020) A tale of two futures: Contrasting scenarios of future precipitation for West Africa from an ensemble of regional climate models. Environ Res Lett 15(6):12. https://doi.org/10.1088/1748-9326/ab7fde
18. Eyring V, Bony S, Meehl GA, Senior CA, Stevens B et al (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci Model Dev

9(5):1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

19. Gano B, Dembele JSB, Tovignan TK, Sine B, Vadez V et al (2021) Adaptation Responses to Early Drought Stress of West Africa Sorghum Varieties. Agronomy 11(3). https://doi.org/10.3390/agronomy11030443
20. GIEC (2014) *Changements climatiques 2014: Rapport de synthèse. Contribution des Groupes de travail I, II et III au cinquième Rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat* (p. 161)
21. Guèye M, Sivakumar MVK (1992) Analyse de la longueur de la saison culturale en fonction de la date de début des pluies au Sénégal. Compte rendu des travaux N°2. ICRISAT, p 42
22. Hersbach H, Bell B, Berrisford P, Dahlgren P, Horányi A et al (2020) The ERA5 Global Reanalysis: Achieving a detailed record of the climate and weather for the past 70 years. *EGU General Assembly Conference Abstracts*. https://doi.org/10.5194/egusphere-egu2020-10375
23. Kadri BK, Halilou H, Karimou I (2019) Culture du mil [*Pennisetum glaucum* (L) R. Br] et ses contraintes à la production. Int J Biol Chem Sci 13(1):503–524. https://doi.org/10.4314/ijbcs.v13i1.40
24. Kholavà J, Hash CT, Kumar pL, Yadav RS, Kocovà M et al (2010) Le millet perlé terminal tolérant à la sécheresse [Pennisetum glaucum (L.) R. Br.] a un ABA foliaire élevé et limite la transpiration à un déficit de pression de vapeur élevé. J Exp Bot 61(5):1431–1440
25. Lobell DB (2014) Climate change adaptation in crop production: Beware of illusions. Global Food Secur 3(2):72–76. https://doi.org/10.1016/j.gfs.2014.05.002
26. Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate Trends and Global Crop Production Since 1980. Science 333(6042):616–620. https://doi.org/10.1126/science.1204531
27. Maraun D (2016) Bias Correcting Climate Change Simulations—A Critical Review. Curr Clim Change Rep 2(4):211–220. https://doi.org/10.1007/s40641-016-0050-x
28. Marteau R, Sultan B, Moron V, Baron C, Traoré SB et al (2010) *Démarrage de la saison des pluies et date de semis du mil dans le sud-ouest du Niger*
29. Mohamed AML, Seyni S, Mkuhlani S, Chemura A, Faye B et al (2025) Impact of climate change on millet yield under different fertilization levels in three agroecological zones of Niger Republic. PLoS ONE 20(10):20. https://doi.org/10.1371/journal.pone.0333963
30. Monerie P-A, Wainwright CM, Sidibe M, Akinsanola AA (2020) Model uncertainties in climate change impacts on Sahel precipitation in ensembles of CMIP5 and CMIP6 simulations. Clim Dyn 55(5):1385–1401. https://doi.org/10.1007/s00382-020-05332-0
31. Nguru W, Mwongera C (2022) *Climate vulnerability assessment for selected crops in Senegal*. https://hdl.handle.net/10568/113688
32. Niang I, Ruppel OC, Abdrabo MA, Ama E, Lennard C et al (2014) Africa. In: Climate Change 2014 : Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Mach et al., pp 1199–1265. Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea

33. Panthou G, Lebel T, Vischel T, Quantin G, Sane Y et al (2018) Rainfall intensification in tropical semi-arid regions: The Sahelian case. Environ Res Lett 13(6):9. https://doi.org/10.1088/1748-9326/aac334
34. Parker L, Bourgoin C, Martinez-Valle A, Läderach P (2019) Vulnerability of the agricultural sector to climate change: The development of a pan-tropical Climate Risk Vulnerability Assessment to inform sub-national decision making. PLoS ONE 14(3). https://doi.org/10.1371/journal.pone.0213641
35. Porkka M, Wang-Erlandsson L, Destouni G, Ekman AML, Rockström J et al (2021) Is wetter better? Exploring agriculturally-relevant rainfall characteristics over four decades in the Sahel. Environ Res Lett 16(3). https://doi.org/10.1088/1748-9326/abdd57
36. Rockström J, Barron J, Brouwer J, Galle S, de Rouw A (1999) On-Farm Spatial and Temporal Variability of Soil and Water in Pearl Millet Cultivation. Soil Sci Soc Am J 63(5):1308–1319. https://doi.org/10.2136/sssaj1999.6351308x
37. Sall AA, Faye E, Guillemin P, Konté O, Saqalli M (2025) Adaptation au climat de variétés de mil et de sorgho dans le Nord-Est du Sénégal: Croisement des paramètres pluviométriques, thermiques et phénologiques. Physio-Géo 21:1–25. https://doi.org/10.4000/13gk4
38. Schlenker W, Lobell DB (2010) Robust negative impacts of climate change on African agriculture. Environ Res Lett 5(1):8. https://doi.org/10.1088/1748-9326/5/1/014010
39. Schultze M, Kankam S, Sanfo S, Fürst C (2024) Agricultural Yield Responses to Climate Variabilities in West Africa: A Food Supply and Demand Analysis. Land 13(3):364. https://doi.org/10.3390/land13030364
40. Sivakumar MVK (1988) Predicting rainy season potential from the onset of rains in Southern Sahelian and Sudanian climatic zones of West Africa. Agric For Meteorol 42(4):295–305. https://doi.org/10.1016/0168-1923(88)90039-1
41. Sultan B, Ahmed AI, Faye B, Tramblay Y (2023) Less negative impacts of climate change on crop yields in West Africa in the new CMIP6 climate simulations ensemble. PLOS Clim 2(12). https://doi.org/10.1371/journal.pclm.0000263
42. Sultan B, Defrance D, Iizumi T (2019) Evidence of crop production losses in West Africa due to historical global warming in two crop models. Sci Rep 9(1):15. https://doi.org/10.1038/s41598-019-49167-0
43. Sultan B, Gaetani M (2016) Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios, and Potential for Adaptation. *Frontiers in Plant Science*, *7*. https://doi.org/10.3389/fpls.2016.01262
44. Sultan B, Roudier P, Quirion P, Alhassane A, Muller B et al (2013) Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. Environ Res Lett 8(1):9. https://doi.org/10.1088/1748-9326/8/1/014040
45. Sy O (2011) *Fiche technique pour la diffusion de variétés de mil et sorgho au Sénégal*. *39*(1), 16
46. Sylla MB, Nikiema PM, Gibba P, Kebe I, Klutse NAB (2016) Climate Change over West Africa: Recent Trends and Future Projections. In J. A. Yaro & J. Hesselberg (Éds.), *Adaptation to Climate Change*

and Variability in Rural West Africa (pp. 25–40). Springer International Publishing. https://doi.org/10.1007/978-3-319-31499-0_3

47. Taguela TN, Akinsanola AA, Adeliyi TE, Rhoades A, Nazarian RH (2025) Understanding drivers and uncertainty in projected African precipitation. Npj Clim Atmospheric Sci 8(1). https://doi.org/10.1038/s41612-025-01123-8
48. Théra K (2017) *Analyse des déterminants génétiques contrôlant la production et la composition de la tige chez le sorgho (Sorghum bicolor [L.] Moench). Intégration des approches bi-et multi-parentales* [Sciences agronomiques et écologie]. Université de Montpellier, Unité de Recherche AGAP
49. Twumasi-Ankrah MJ, Zhan J, Yeboah FK, Xu L, Kumi MA et al (2025) Vulnerability of agroecosystems to climate change in the Sahel. *Agricultural Systems*, *226*. https://doi.org/10.1016/j.agsy.2025.104327
50. Upadhyaya HD, Pundir RPS, Gowda CLL, Reddy G, V., and, Singh S (2008) Establishing a core collection of foxtail millet to enhance the utilization of germplasm of an underutilized crop. Plant Genetic Resour 7(2):177–184. https://doi.org/10.1017/S1479262108178042
51. Wainwright CM, Black E, Allan RP (2021) *Future Changes in Wet and Dry Season Characteristics in CMIP5 and CMIP6 Simulations*. https://doi.org/10.1175/JHM-D-21-0017.1
52. Yang K, Wang G, Cai W, Mohino E, Rodriguez-Fonseca B et al (2025) Increased interannual variability of Sahel rainfall under greenhouse warming. Nat Commun 17(1):1125. https://doi.org/10.1038/s41467-025-67885-0

Figures

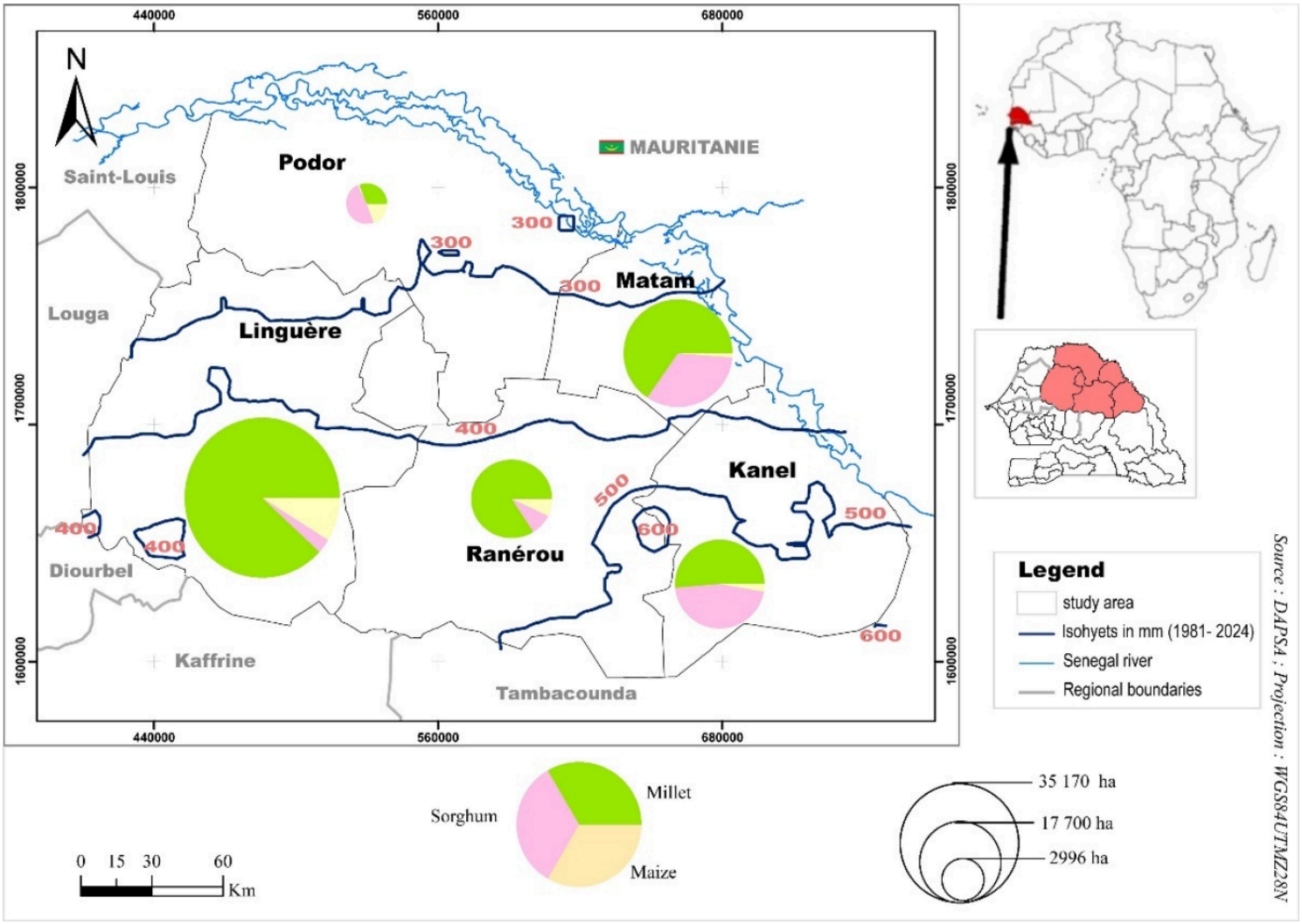


Figure 1

Location and distribution of the main rain-fed crops, as well as the rainfall gradient (isohyets) in north-eastern Senegal. The five departments studied (Podor, Matam, Kanel, Ranérou and Linguère) are shown, along with the distribution of their areas under cultivation for millet (green), sorghum (pink) and maize (yellow). The size of the pie charts is proportional to the total area under cultivation. The dark blue lines represent the isohyets (mm), illustrating the increasing rainfall gradient from north to south. The river network of the Senegal River is shown in light blue. Source: Direction de l'Analyse, de la Prévention et des Statistiques Agricoles, 2022; WGS 84 projection / UTM Zone 28N

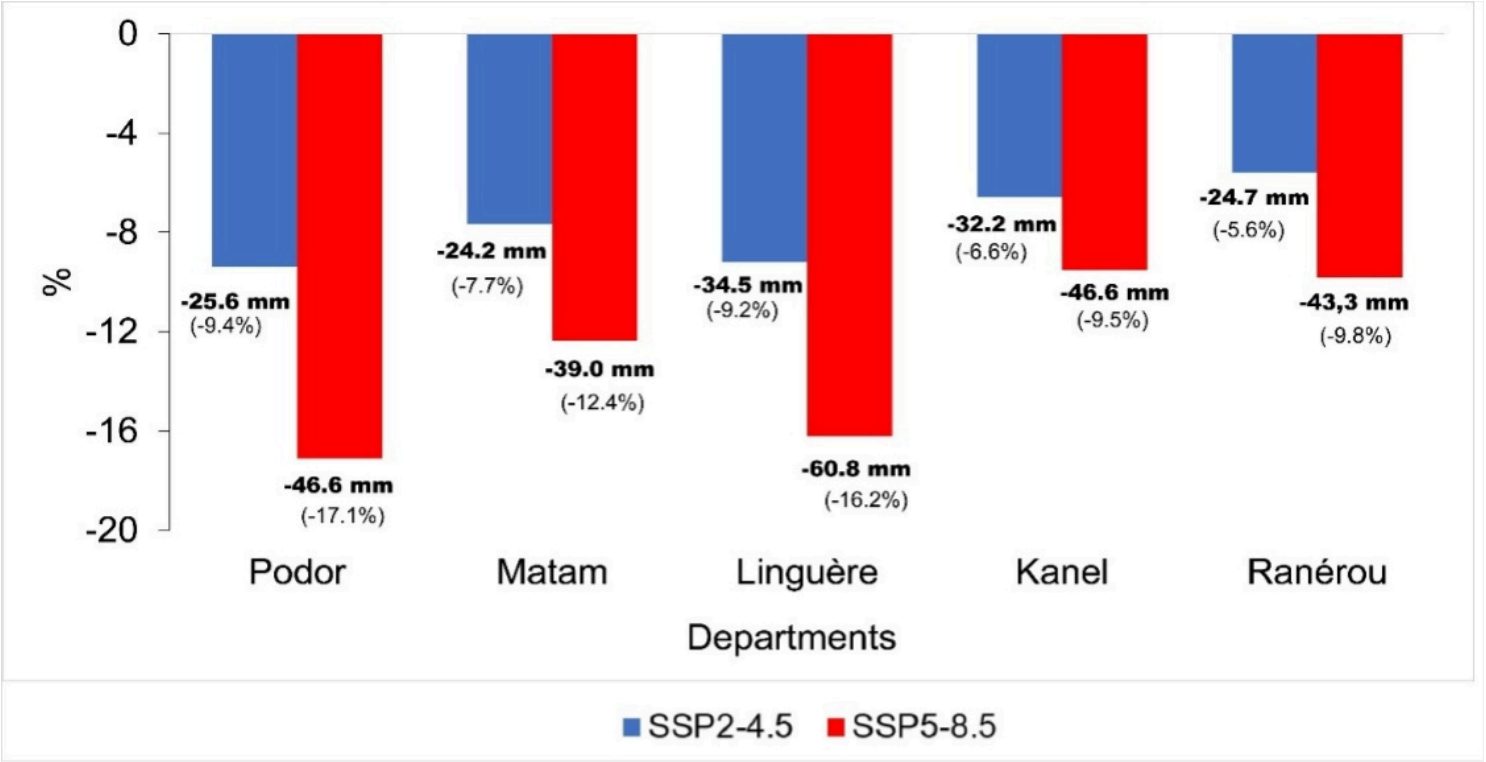


Figure 2

Anomalies in projected annual rainfall totals in north-eastern Senegal under the SSP2-4.5 and SSP5-8.5 scenarios (2025-2050) compared with the historical period (1981-2010). The blue and red bars represent the anomalies under the SSP2-4.5 and SSP5-8.5 scenarios, respectively. The values indicate the absolute (mm) and relative (%) deviation from the 1981-2010 historical mean. Source: corrected CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025-2050); CHIRPS historical reference (1981-2010)

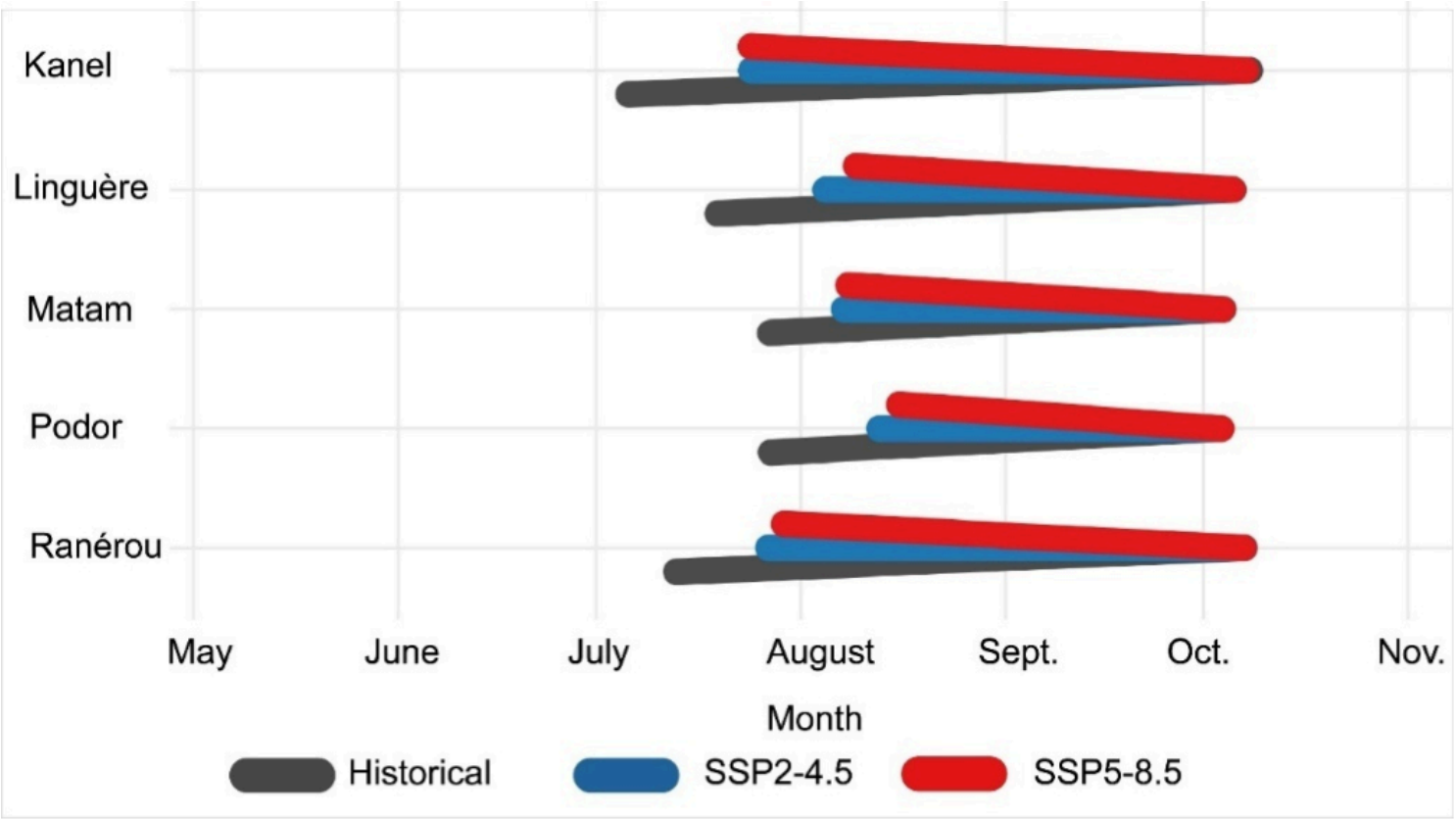


Figure 3

Average timing of the rainy season in north-eastern Senegal for the historical period (1981-2010) and climate projections (2025-2050) under the SSP2-4.5 and SSP5-8.5 scenarios. The bars represent the average seasonal window defined by the average start and end dates of the season. Start of season: (Guèye and Sivakumar, 1992) *criterion; end of season: simplified water balance* (Allan *et al.*, 1998). *Source: corrected CNRM–CM6–1 + MPI–ESM1–2–HR ensemble (projections, 2025-2050); CHIRPS historical reference (1981-2010)*

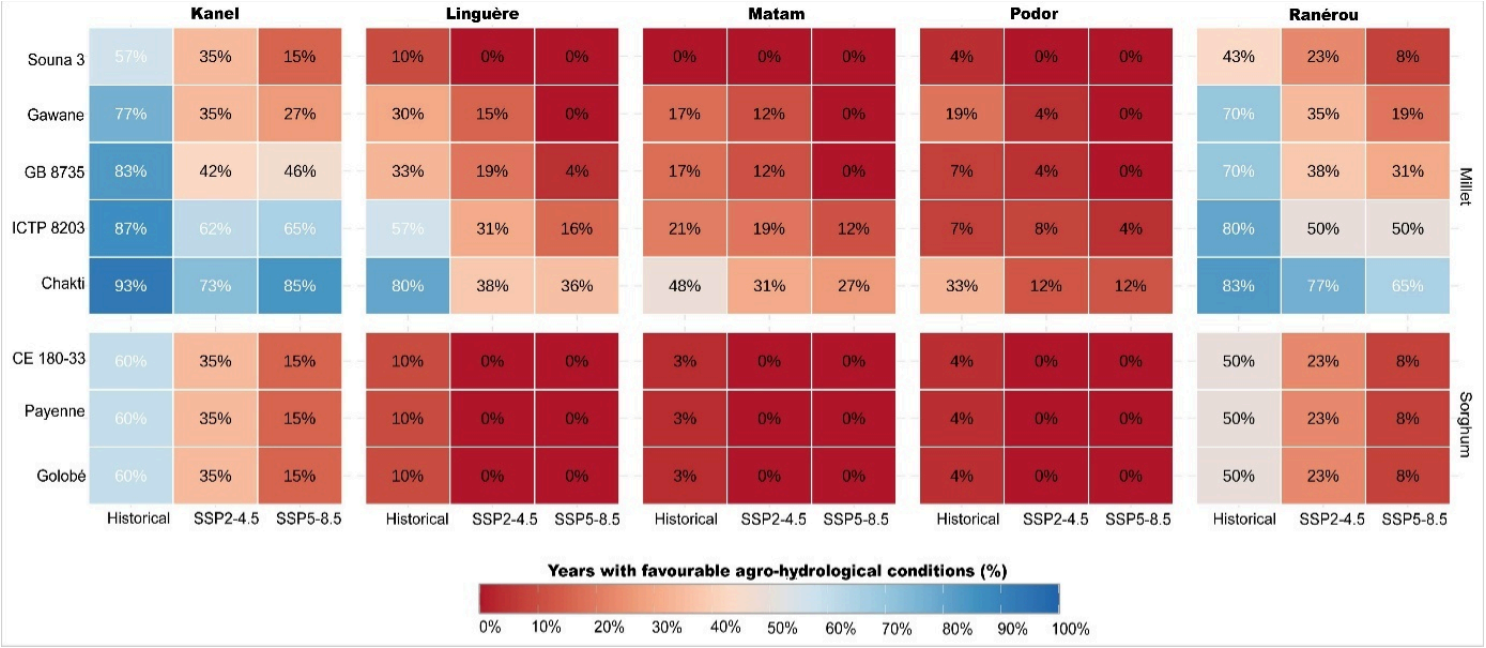


Figure 4

Overall agro-hydrological suitability of millet and sorghum varieties in north-eastern Senegal (historical data 1981-2010 and projections 2025-2050). The values indicate the percentage of years in which the duration of the rainy season covers the variety's growth cycle and the annual cumulative rainfall meets the minimum water requirement of each variety. The colour scale ranges from red (poor suitability) to blue (good suitability). Source: CHIRPS (historical data); CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025-2050)

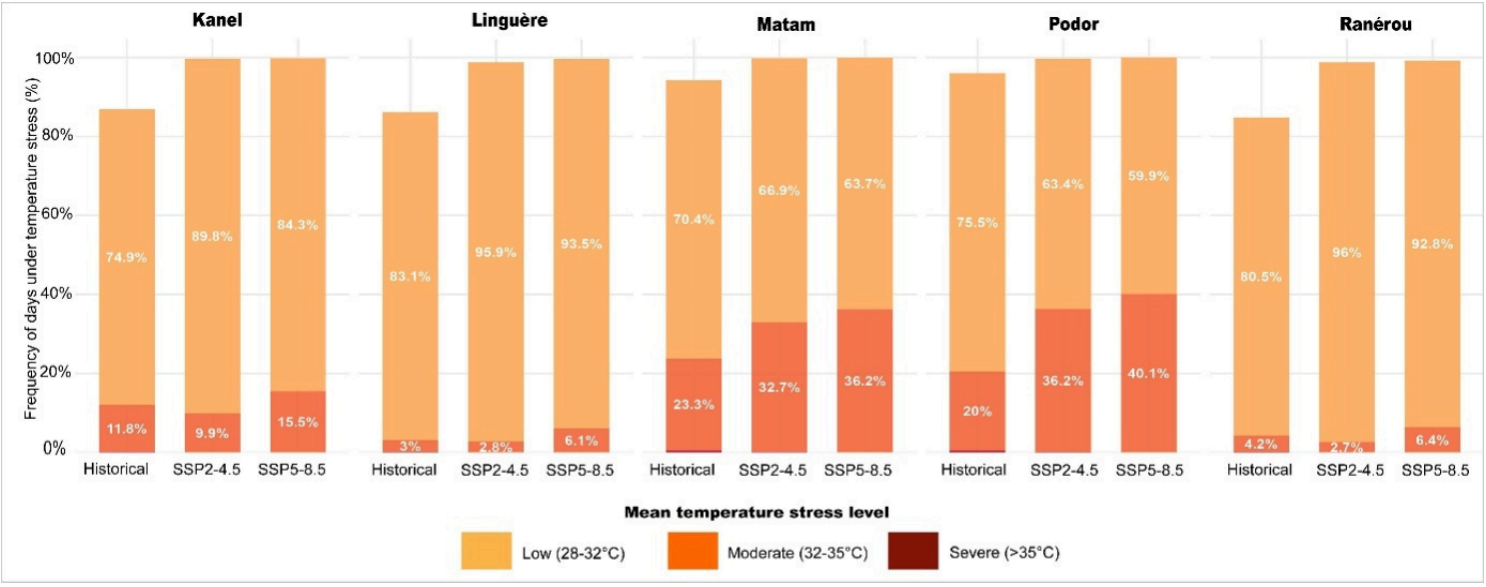


Figure 5

Frequency of days with thermal stress on the mean temperature (Tmoy) during the rainy season in north-eastern Senegal (1981-2010 historical data and 2025-2050 projections). Only days with thermal stress on

the mean temperature (Tmoy > 28 °C) are shown. Frequencies are expressed as a percentage of the total number of days in the rainy season. Low stress: 28 °C < Tmoy ≤ 32 °C; moderate stress: 32 °C < Tmoy ≤ 35 °C; severe stress: Tmoy > 35 °C. Source: ERA5-Land (historical); corrected CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025-2050)

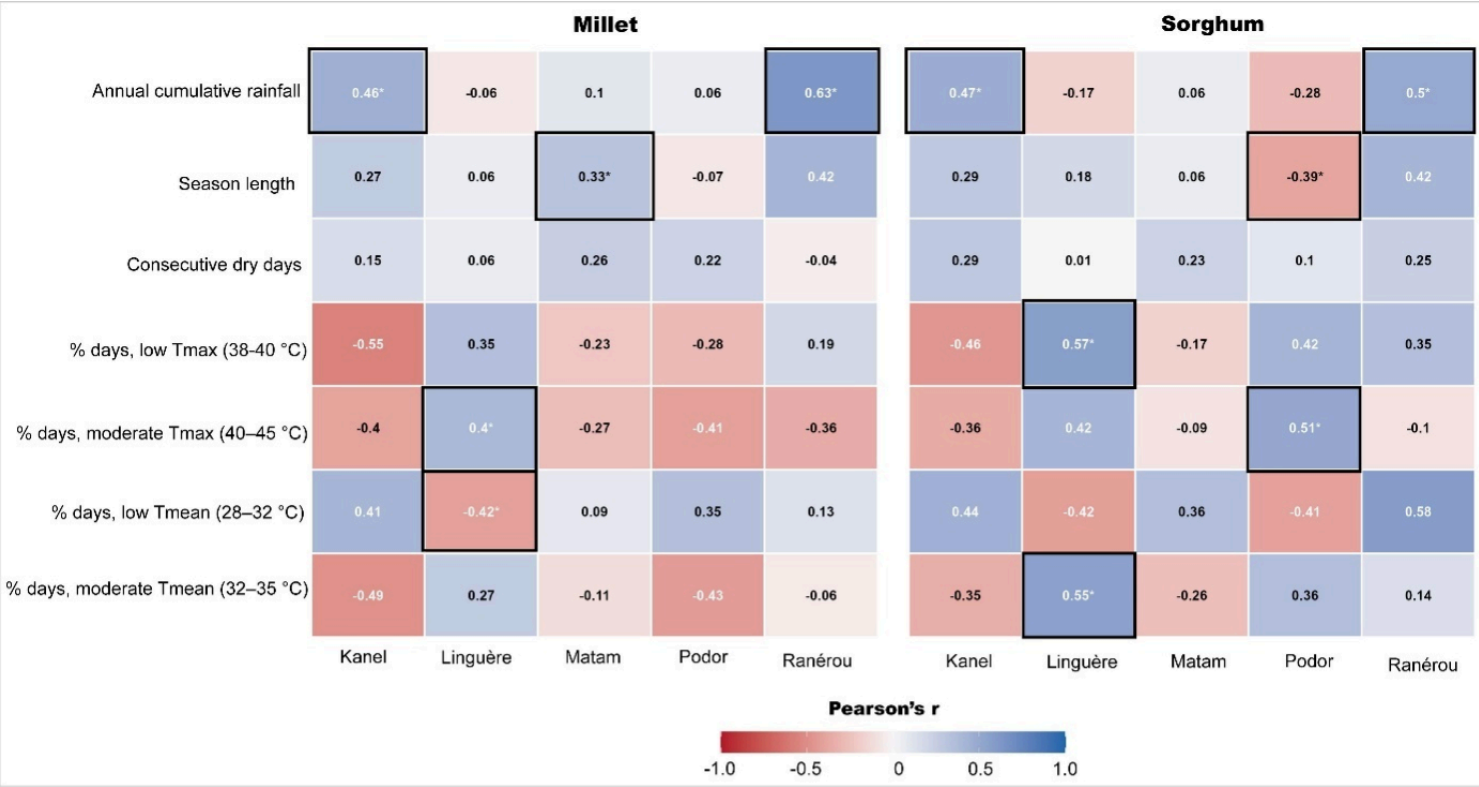


Figure 6

Correlations between millet and sorghum yields and climate indicators in north-eastern Senegal (1981-2022). The values correspond to Pearson's correlation coefficients between annual yields and each climate indicator, by department and by crop. The boxes framed in black and marked with an asterisk indicate statistically significant correlations at the 5% significance level. Blue indicates a positive correlation and red a negative correlation. Thermal constraints: low and moderate for Tmax (38-40 °C and 40-45 °C) and for Tmoy (28-32 °C and 32-35 °C). Source: DAPSA yield data (1981-2022); CHIRPS and ERA5-Land (1981-2022).

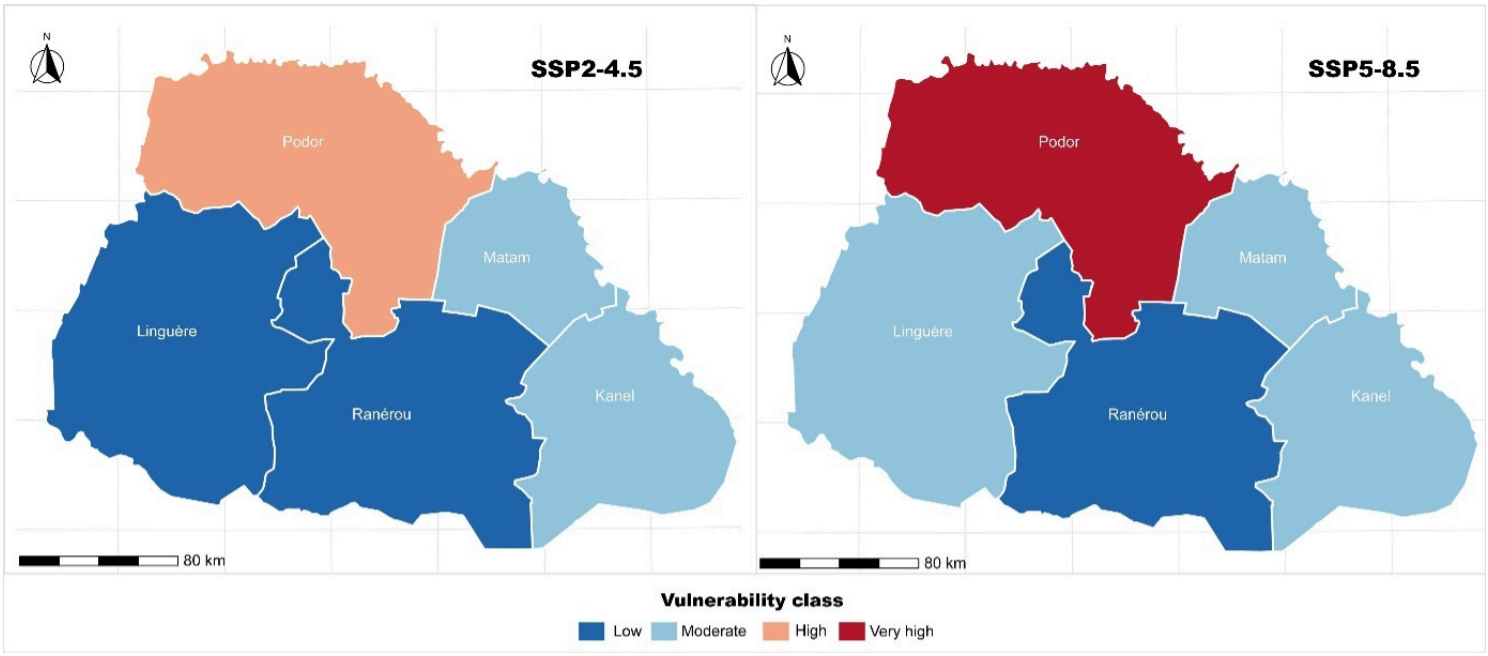


Figure 7

Vulnerability classes for millet and sorghum cropping systems in the five north-eastern departments of Senegal for the period 2025-2050, according to the SSP2-4.5 (left) and SSP5-8.5 (right) scenarios. Agroclimatic vulnerability classes established using a composite index combining exposure and sensitivity in equal parts. Exposure incorporates the projected trends in cumulative rainfall, the shortening of the growing season, dry spells and thermal constraints (Tmax and Tmoy). Sensitivity is based on historical agroclimatic conditions: water deficit relative to the water requirements of millet and sorghum, and the frequency of thermal constraints on the mean temperature. The index, calculated for the period 2025-2050 relative to the 1981-2010 reference period for climate variables and the 1981-2022 reference period for yields, is divided into four classes: low (dark blue), moderate (light blue), high (salmon) and very high (red). Source: corrected CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025-2050).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- OnlineResource1.pdf