Online Resource 1

Supplementary data, methods and results

Article title: Projected agroclimatic changes and the vulnerability of rain-fed cereal systems in north-eastern Senegal

Journal: *Regional Environmental Change*

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This file gathers the material cited in the main text as Online Resource 1 (Text S1–S9, Tables S1–S3 and Figs. S1–S7).

Text S1. Agricultural context and production systems

From a socio-economic perspective, agriculture is the backbone of the regional economy. It is the primary source of employment and income for the majority of rural households, in a context characterised by a weak industrial, commercial and tourism sector. The main rain-fed cereals grown are millet, sorghum and maize (Zea mays), with millet clearly dominating. Millet accounts for the largest share of the area under cultivation, particularly in the departments of Linguère and Ranérou, where it represents over 70% of the cultivated area. By contrast, sorghum dominates in the departments of Podor, Matam and Kanel. Maize, meanwhile, remains marginal across the entire area, with the exception of Linguère, where it accounts for around 15% of the area under cultivation.

Furthermore, production systems exhibit a diversity linked to the presence of the River Senegal. The departments of Podor, Matam and Kanel combine rain-fed agriculture with flood-recession crops, grown on land left exposed after the water recedes, as well as with irrigated areas established along the valley. Conversely, Linguère and Ranérou, which are situated further from the river, 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.

Text S2. Climate data processing, bias correction and model-specific projections

Daily precipitation data (1981-2024) are sourced from the CHIRPS Daily product (Climate Hazards Group InfraRed Precipitation with Station data), accessible via Google Earth Engine (GEE). This product combines satellite data and in situ measurements at a resolution of approximately 0.05° (~5 km) (Funk *et al.*, 2015) and performs well for seasonal and annual totals in West Africa (Dinku *et al.*, 2018; Satge *et al.*, 2020), although it tends to underestimate extreme rainfall and may exhibit biases in areas with low observation density (Toté *et al.*, 2015).

Daily maximum and minimum temperatures (1981-2024) were extracted from the ERA5-Land reanalysis (European Centre for Medium-Range Weather Forecasts (ECMWF)), providing data at 2 m above ground level with a resolution of approximately 9 km (Hersbach *et al.*, 2020). ERA5-Land generally exhibits biases of less than 1 °C for daily temperatures in sub-Saharan Africa (Muñoz-Sabater *et al.*, 2021), but its resolution may smooth out certain local gradients.

Annual precipitation totals and annual temperature averages (converted from K to °C) were calculated from the grids and then aggregated at departmental level by taking the arithmetic mean of the pixels within each administrative boundary, using `ee.Reducer.mean()` in GEE.

The projections are drawn from the NASA NEX-GDDP-CMIP6 collection (resolution ≈ 25 km). Two models were selected: CNRM-CM6-1 and MPI-ESM1-2-HR, covering the period 2025-2050 for the SSP2-4.5 and SSP5-8.5 scenarios. CNRM-CM6-1 was chosen for its good performance in simulating the

West African monsoon (Almazroui *et al.*, 2020; Dosio *et al.*, 2020), and MPI-ESM1-2-HR for its high resolution and performance in West Africa (Taguela *et al.*, 2025). The use of two models helps to reduce the uncertainty associated with using a single model (Tebaldi and Knutti, 2007), whilst not, however, covering the full range of inter-model dispersion in the CMIP6 archive.

The variables used are daily precipitation (pr, kg m^{-2} s^{-1}) and daily maximum and minimum temperatures (tasmax, tasmin, in Kelvin). Precipitation was converted to mm/day and then summed annually, whilst temperatures were averaged annually and converted to degrees Celsius, before being aggregated at departmental level by averaging the pixels.

The daily time series were corrected using the Quantile Delta Mapping (QDM) method, implemented in the R package MBC. QDM preserves projected changes in quantiles whilst adjusting the distribution of the simulated data (Cannon *et al.*, 2015; Maraun, 2016). The 1981-2010 reference period was used for the adjustment, with CHIRPS as the reference for precipitation and ERA5-Land for temperatures. The correction was applied separately by department, distinguishing between dry and wet days for precipitation and treating tasmax and tasmin independently. An ensemble average was then calculated from the corrected projections of the two models and used for all climatic and agroclimatic analyses. The convergence of the two models regarding the sign of the projected changes was verified beforehand; the values for each model are provided in the supplementary material.

Table S1. Mean annual rainfall by department, scenario and model

Mean annual rainfall (mm yr^{-1}). Historical: CHIRPS, 1981–2010; projections: 2025–2050. The ensemble relative anomaly is the change in the two-model ensemble mean relative to the historical mean.

Department	Scenario	Historical (mm yr^{-1})	CNRM-CM6-1	MPI-ESM1-2-HR	Ensemble mean	Ensemble relative anomaly (%)
Kanel	SSP2-4.5	490.0	425.0	490.7	457.8	-6.6
	SSP5-8.5	490.0	430.1	456.8	443.4	-9.5
Linguère	SSP2-4.5	375.3	327.9	353.8	340.8	-9.2
	SSP5-8.5	375.3	301.1	328.0	314.5	-16.2
Matam	SSP2-4.5	315.5	272.9	309.7	291.3	-7.7
	SSP5-8.5	315.5	263.6	289.4	276.5	-12.4
Podor	SSP2-4.5	272.6	234.5	259.5	247.0	-9.4
	SSP5-8.5	272.6	218.3	233.7	226.0	-17.1
Ranérou	SSP2-4.5	441.2	389.6	443.5	416.5	-5.6
	SSP5-8.5	441.2	378.5	417.3	397.9	-9.8

Table S2. Mean temperature by department, scenario and model

Mean temperature (°C). Historical: ERA5-Land, 1981–2010; projections: 2025–2050. The ensemble anomaly is the change in the two-model ensemble mean relative to the historical mean.

Department	Scenario	Historical (°C)	CNRM-CM6-1	MPI-ESM1-2-HR	Ensemble mean	Ensemble anomaly (°C)
Kanel	SSP2-4.5	30.36	31.90	31.34	31.62	+1.26
	SSP5-8.5	30.36	32.09	31.59	31.84	+1.48
Linguère	SSP2-4.5	28.92	30.30	29.95	30.12	+1.21
	SSP5-8.5	28.92	30.58	30.05	30.31	+1.40
Matam	SSP2-4.5	30.46	31.95	31.50	31.73	+1.27
	SSP5-8.5	30.46	32.16	31.71	31.94	+1.48
Podor	SSP2-4.5	29.81	31.19	30.86	31.02	+1.21
	SSP5-8.5	29.81	31.42	30.99	31.21	+1.39
Ranérou	SSP2-4.5	29.52	31.00	30.53	30.77	+1.25
	SSP5-8.5	29.52	31.25	30.71	30.98	+1.47

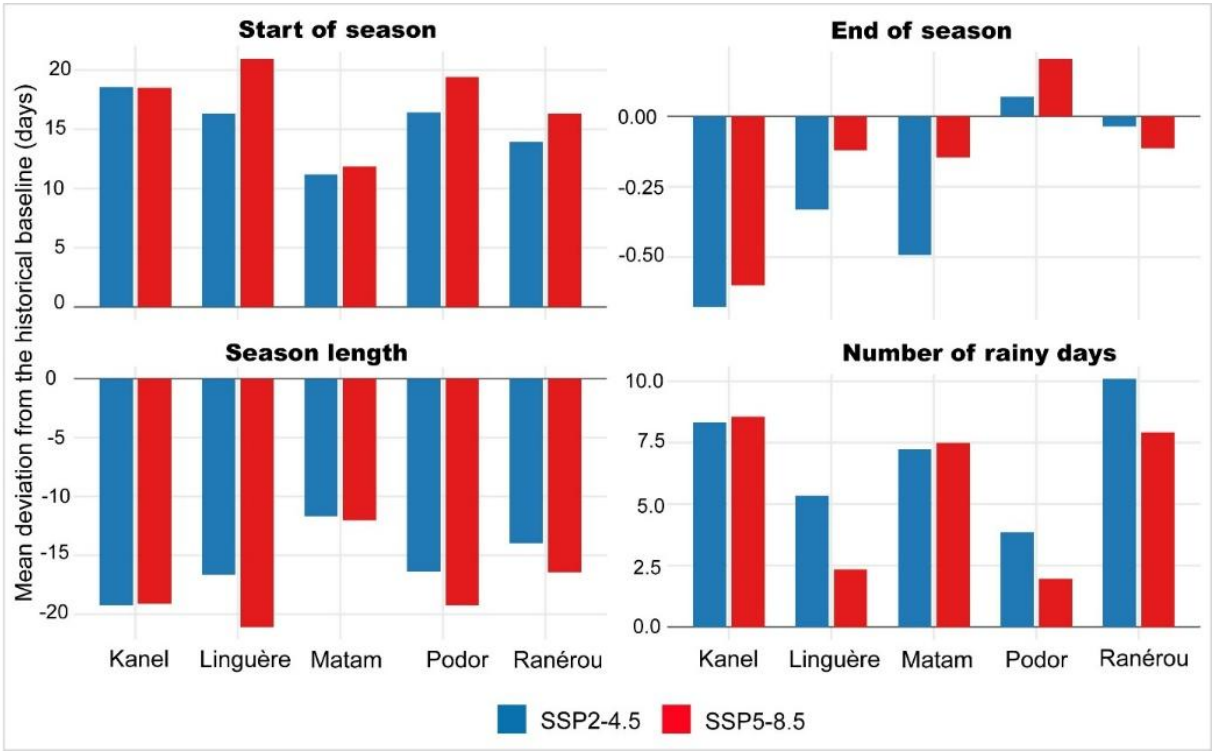


Fig. S1 Projected anomalies in seasonal window indicators in north-eastern Senegal under the SSP2-4.5 and SSP5-8.5 scenarios (2025-2050) compared with the historical period (1981-2010). The anomalies correspond to the difference between the projected mean (2025-2050) and the historical mean (1981-2010). Positive values for the start of the season and the number of rainy days indicate a later start to the season and an increase in the number of rainy days. Negative values for duration and end of season indicate a shortening and an earlier end, respectively. Source: corrected CNRM–CM6–1 + MPI–ESM1–2–HR ensemble (projections, 2025-2050); historical reference: CHIRPS (1981-2010)

Table S3. Average characteristics of the rainy season in north-eastern Senegal for the historical period (1981-2010) and the projections (2025-2050)

Department	Scenario	Rainy season start date	Rainy season end date	Rainy season duration	Number of rainy days
Kanel	Historical	4 July	7 October	95 days	46 days
	SSP2-4.5	23 July	6 October	76 days	54 days
	SSP5-8.5	23 July	6 October	76 days	54 days
Linguère	Historical	23 July	4 October	79 days	36 days
	SSP2-4.5	3 August	4 October	63 days	42 days
	SSP5-8.5	8 August	4 October	58 days	39 days
Matam	Historical	26 July	3 October	70 days	29 days
	SSP2-4.5	6 August	2 October	58 days	36 days
	SSP5-8.5	7 August	2 October	58 days	36 days
Podor	Historical	26 July	2 October	69 days	28 days
	SSP2-4.5	11 August	2 October	53 days	32 days
	SSP5-8.5	14 August	2 October	50 days	30 days
Ranérou	Historical	12 July	6 October	87 days	41 days
	SSP2-4.5	26 July	6 October	73 days	51 days
	SSP5-8.5	28 July	6 October	71 days	49 days

Source: CHIRPS (historical data); CNRM-CM6-1 + MPI-ESM1-2-HR ensemble, corrected using the QDM method (projections).

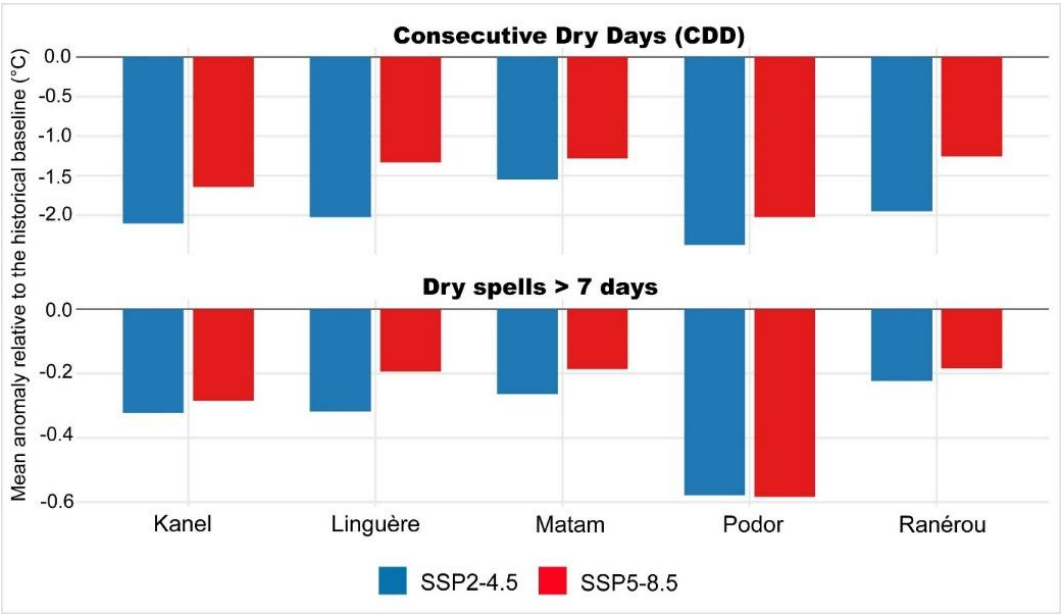


Fig. S2 Projected anomalies in intraseasonal dry spells in north-eastern Senegal under the SSP2-4.5 and SSP5-8.5 scenarios (2025-2050) compared with the historical period (1981-2010). The anomalies correspond to the difference between the projected mean (2025-2050) and the historical mean (1981-2010). CDD: maximum number of consecutive dry days during the rainy season (dry day: precipitation < 1 mm). Negative values indicate a reduction in dry spells. Source: corrected CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025-2050); historical reference: CHIRPS (1981-2010)

Text S3. Projected temperature anomalies by department

Climate projections indicate widespread and spatially uniform warming across all departments in north-eastern Senegal by 2050, regardless of the scenario considered. Increases in maximum temperature range from +1.25 °C in Linguère to +1.30 °C in Matam under SSP2-4.5, and from +1.47 °C in Podor to +1.52 °C in Ranérou under SSP5-8.5 (Fig.6). The differences between scenarios are small but consistent, averaging around +0.22 °C, in line with the difference in radiative forcing between SSP2-4.5 and SSP5-8.5.

Minimum temperature anomalies show a slightly more varied spatial distribution. Under SSP2-4.5, the increases range from +1.16 °C in Linguère and Podor to +1.25 °C in Kanel, with intermediate values in Matam and Ranérou. Under SSP5-8.5, the anomalies range from +1.29 °C in Linguère to +1.47 °C in Kanel, whilst Podor, Matam and Ranérou show intermediate increases. Linguère and Podor consistently record the smallest increases in minimum temperature under both scenarios, with a difference of around 0.10 °C compared with the other departments. The difference between the scenarios is more pronounced for minimum temperatures than for maximum temperatures, reaching +0.22 °C in Kanel and Matam compared with +0.13 °C in Linguère.

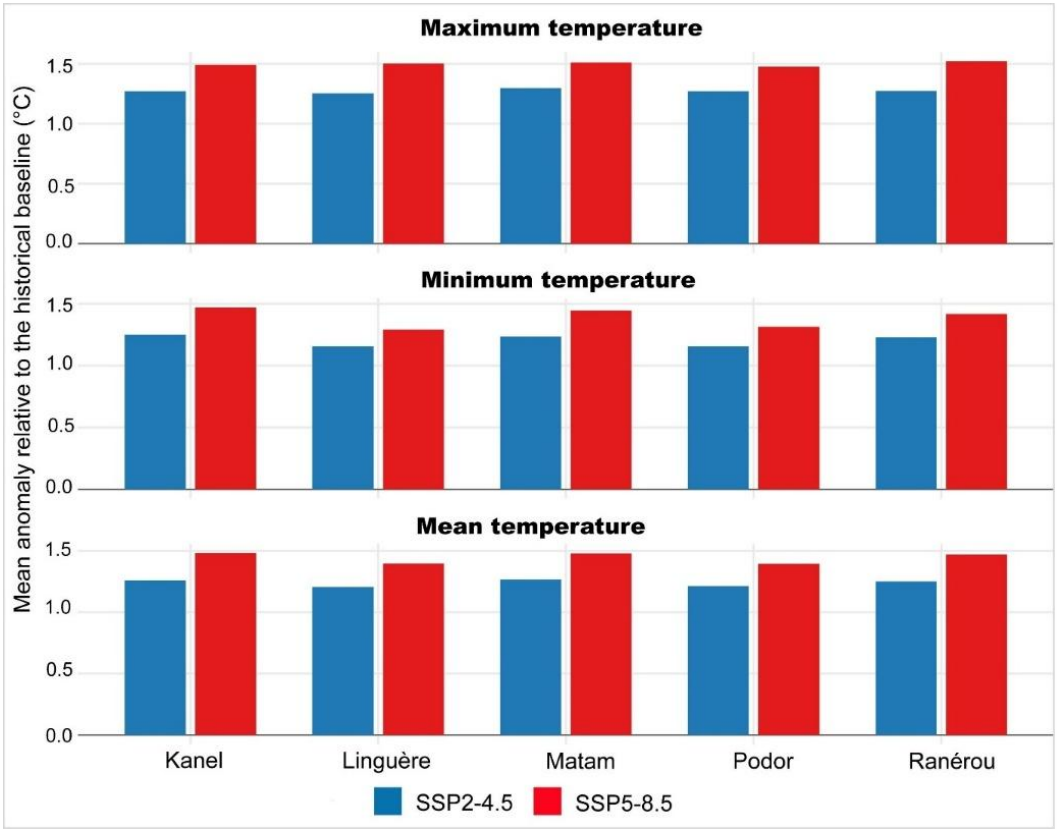


Fig. S3 Projected average anomalies in maximum, minimum and mean temperatures in north-eastern Senegal under the SSP2-4.5 and SSP5-8.5 scenarios (2025-2050), relative to the reference period (1981-2010). The blue and red bars represent the anomalies under SSP2-4.5 and SSP5-8.5 respectively. The anomalies correspond to the difference between the projected interannual mean (2025-2050) and the historical mean (1981-2010). Source: CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025-2050); historical reference: ERA5-Land (1981-2010)

Text S4. Match between rainy-season duration and varietal cycles

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. For millet, the historical period is most favourable in Kanel, where compatibility rates are high for all varieties, reaching 75% for long-cycle varieties such as Souna 3 and Gawane, and exceeding 75% for short-cycle varieties such as ICTP 8203 and Chakti. Ranérou also shows satisfactory suitability rates for short-cycle varieties, though these are lower than those at Kanel. Linguère records intermediate rates for short-cycle varieties, whilst Matam and Podor show the lowest rates, particularly for long-cycle varieties, where historical values remain below 25%. Under SSP2-4.5, suitability rates fall across all departments; under SSP5-8.5, they plummet to below 25% for all varieties in Matam and Podor, whilst in Kanel and Ranérou, short-cycle varieties such as Chakti and ICTP 8203 maintain rates above 50% under SSP2-4.5 before declining under SSP5-8.5 (Fig. S4).

For sorghum, historical rates are generally lower than those for millet. Kanel is the only department where historical rates exceed 70% for all sorghum varieties; Ranérou shows modest rates and the other departments very low values (below 25% for all varieties). Under the projected scenarios, sorghum suitability rates deteriorate sharply across the board, reaching values close to zero under SSP5-8.5 in Linguère, Matam and Podor (Fig. S4).

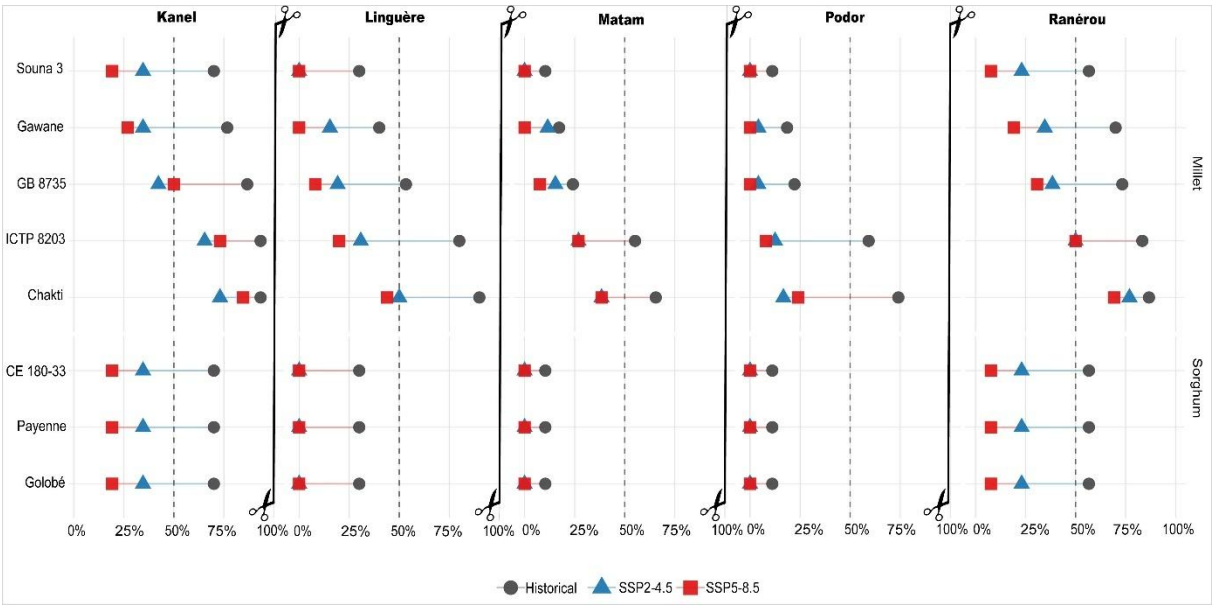


Fig. S4 Alignment between the duration of the rainy season and the growth cycles of millet and sorghum in north-eastern Senegal (historical data 1981-2010 and projections 2025-2050). The percentage indicates the proportion of years in which the duration of the rainy season covers the full growing cycle of each variety. The vertical dotted line at 50% represents the threshold above which the growing cycle is covered in the majority of years. The grey circles represent the historical period, the blue triangles the SSP2-4.5 scenario and the red squares the SSP5-8.5 scenario. Source: CHIRPS (historical); corrected CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025-2050)

Text S5. Satisfaction of the minimum water requirement

The ability to meet the minimum water requirement is also deteriorating across all departments. For millet, Kanel has historically been the best-supplied, with satisfaction rates reaching 100% for varieties with the lowest minimum water requirement (Chakti and Gawane, 300 mm) and 90% for varieties with higher requirements (GB 8735 and ICTP 8203, 350 mm). Ranérou has historically high satisfaction rates for the least water-demanding varieties (93%) but more moderate rates for Souna 3 (57%). Linguère shows intermediate historical rates ranging from 27% for Souna 3 to 87% for Chakti and Gawane. Matam and Podor record the lowest rates, with historical values not exceeding 53% for the least demanding varieties and falling to 3% for Souna 3 at Podor. Under SSP2-4.5 and SSP5-8.5, the rates decrease across the board; in Kanel, they remain relatively high under SSP2-4.5 (85-92% for the least demanding varieties) but fall under SSP5-8.5, whilst in Podor they plummet to very low levels under both scenarios (4-19% under SSP2-4.5 and 4–12% under SSP5-8.5) (Fig. S5).

For sorghum, for which the minimum requirement is uniformly set at 400 mm, the satisfaction rates are identical across varieties within the same department. Historically, Kanel recorded a rate of 83%, Ranérou 73%, Linguère 30%, Matam 10% and Podor 3%. Under SSP2-4.5 and subsequently SSP5-8.5, these rates decline across all departments, with a particularly sharp decline in Linguère, Matam and Podor (Fig. S5).

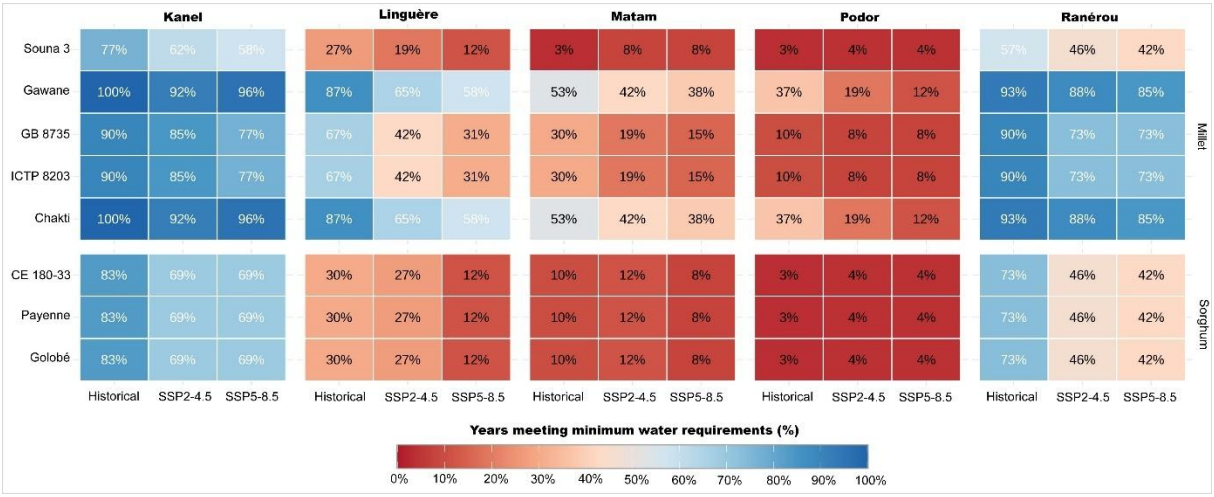


Fig. S5 Satisfaction of the minimum water requirement for millet and sorghum varieties in north-eastern Senegal (historical data 1981-2010 and projections for 2025-2050). The values indicate the percentage of years in which the cumulative annual rainfall meets the minimum water requirement for each variety. The colour scale ranges from red (low coverage) to blue (good coverage). Minimum water requirement for millet: Chakti and Gawane = 300 mm; ICTP 8203 and GB 8735 = 350 mm; Souna 3 = 420 mm. Minimum sorghum requirement: CE 180-33, Payenne and Golobé = 400 mm. Source: CHIRPS (historical data); corrected CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025–2050).

Text S6. Thermal stress based on maximum temperature (Tmax)

Thermal stresses related to maximum temperatures remain generally moderate during the rainy season. Historically, Matam and Podor have the highest frequencies (around 14% of days with Tmax ≥ 38 °C), whilst Kanel, Linguère and Ranérou show values below 7%. No severe constraints (Tmax > 45 °C) are observed. Under SSP2-4.5, trends vary. All departments show a slight reduction compared with the historical period. Under SSP5-8.5, the stress intensifies in all departments, with a total frequency reaching 18.6% in Podor and 14.5% in Matam, whilst Linguère, Kanel and Ranérou remain below 4%. No severe stress occurs under either scenario (Fig. S6).

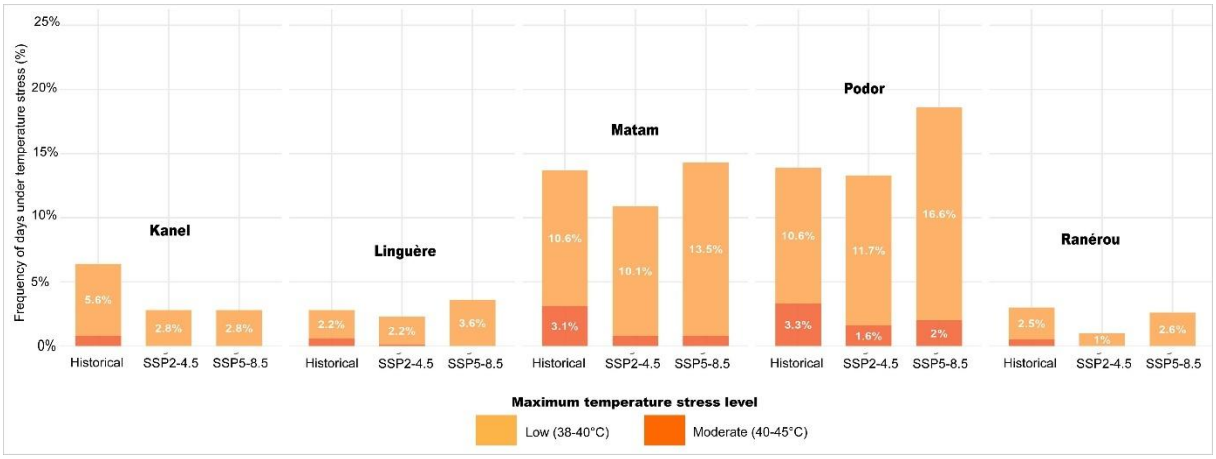


Fig. S6 Frequency of days with thermal stress based on maximum temperature (Tmax) during the rainy season in north-eastern Senegal (1981-2010 historical data and 2025-2050 projections). Only days with thermal stress (Tmax ≥ 38 °C) are shown. Frequencies are expressed as a percentage of the total number of days in the rainy season. Low heat stress: 38 °C ≤ Tmax ≤ 40 °C; moderate heat stress: 40 °C < Tmax ≤ 45 °C; severe heat stress: Tmax > 45 °C. Source: ERA5-Land (historical); corrected CNRM-CM6-1 + MPI-ESM1-2-HR ensemble (projections, 2025-2050)

Text S7. Interannual variability of millet and sorghum yields

Analysis of yield anomalies for millet and sorghum over the period 1981-2022 reveals marked interannual variability and contrasting trends across departments (Fig. S7). In Kanel and Ranérou, a clear visual correlation is observed between positive rainfall anomalies and positive yield anomalies, particularly around the years 2009-2010, which were characterised by significant rainfall surpluses and yields well above the average for both crops.

In Podor and Matam, the correlation between rainfall anomalies and yield anomalies is less pronounced. In Podor in particular, sorghum yields exhibit high interannual variability that does not systematically follow rainfall fluctuations. Matam has seen a few exceptional years for sorghum yields, notably in 1982 and 1997, despite negative rainfall anomalies. In Linguère, yield variability remains moderate, with a regular alternation of years of surplus and deficit, without any clear directional trend over the period studied.



Fig. S7 Year-on-year anomalies in millet and sorghum yields and rainfall anomalies in north-eastern Senegal (1981-2022). Yield anomalies for millet (top panel) and sorghum (bottom panel) by department. Green bars: years with above-average yields; red bars: years with below-average yields. Blue line: annual rainfall anomaly (mm, secondary axis). Source: DAPSA (1981-2022) and CHIRPS (1981-2022)

Text S8. Correlations between yields and thermal indicators

Thermal stress yields five significant correlations, all of which are found in Linguère and Podor, and are predominantly positive. In Linguère, the frequency of days with moderate thermal stress on the maximum temperature is positively correlated with millet yields ($r = +0.40$), whilst the frequencies of mild thermal stress on the maximum temperature ($r = +0.57$) and moderate thermal stress on the mean temperature ($r = +0.55$) are positively correlated with sorghum yields; only low stress on the mean temperature shows a negative correlation with millet yields ($r = -0.42$). In Podor, moderate thermal stress on the maximum temperature is positively correlated with sorghum yields ($r = +0.51$).

Text S9. Robustness of the vulnerability ranking to the choice of weightings

The robustness of this hierarchy with respect to the choice of weightings was verified by recalculating the index under three alternative schemes: equal weights across the eight components, a greater weighting for exposure (70%) and a greater weighting for sensitivity (70%). The rankings obtained remain strongly correlated with that of the chosen weighting (Spearman's rank correlation ranging from 0.8 to 1 depending on the scenario and scheme). Podor consistently emerges as the most vulnerable department, and Matam occupies second place in almost all configurations; only the order of the least vulnerable departments (Kanel, Linguère and Ranérou), whose scores are similar, varies slightly, without any of them changing vulnerability class. The spatial hierarchy obtained therefore does not depend on the specific choice of weightings.

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