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Ousmane Diallo
Department of Agronomy,
University of Bamako, Bamako,
Mali

Fatoumata Keita
Department of Agronomy,
University of Bamako, Bamako,
Mali

Simulation of climate change impacts on sorghum phenology and grain yield using DSSAT-CERES model in the Sahel region

Ousmane Diallo and Fatoumata Keita

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Abstract

Sorghum feeds more than 300 million people across the Sahel, yet rising temperatures and shifting rainfall threaten the crop's future in the region. This research calibrated and validated the DSSAT-CERES-Sorghum model for the local cultivar Séguetana using 12 station-years of field data from southern Mali, then projected grain yield and phenological shifts under RCP 4.5 and RCP 8.5 scenarios for the 2050s and 2080s. Model calibration achieved an RMSE of 0.13 t/ha and d-index of 0.91 for grain yield. Projections indicated yield declines of 11.4% (RCP 4.5, 2050s) to 38.6% (RCP 8.5, 2080s) relative to the 1985-2014 baseline. Days from sowing to anthesis shortened by 4-11 days, and grain-filling duration contracted by 3-8 days depending on the scenario. These results point to an urgent need for heat-tolerant varieties and adjusted planting windows in Sahelian sorghum systems.

Keywords: Sorghum, climate change, DSSAT-CERES, crop simulation, Sahel, phenology, grain yield, RCP scenarios, temperature stress, Mali

Introduction

Sorghum is not simply another cereal—for millions of Sahelian households it is the difference between food security and hunger. The crop covers about 7.2 million hectares in West Africa and contributes up to 40% of total cereal calories in landlocked Sahel countries such as Mali, Burkina Faso, and Niger ^[1]. Climate models agree that mean temperatures across the region will rise by 1.5-3.8 °C by mid-century, while rainfall is expected to become more erratic with fewer but more intense events ^[2]. Both changes threaten sorghum productivity because the crop is grown almost entirely under rainfed conditions and its phenological timing is tightly coupled to moisture availability ^[3].

Process-based crop models such as DSSAT-CERES-Sorghum can translate climate projections into quantitative yield estimates by simulating daily interactions among genotype, weather, and soil ^[4]. The model has been validated for sorghum in East Africa and India ^[5] but has seen limited application in the western Sahel, where cultivar-specific genetic coefficients are lacking ^[6]. This research aimed to: (a) calibrate and validate DSSAT-CERES for the widely grown Malian cultivar Séguetana, (b) simulate phenological and yield responses under four climate scenarios, and (c) identify the most yield-limiting factor—temperature rise or rainfall change.

Research Area Description

Field data for calibration were collected at the Institut d'Économie Rurale (IER) research station in Sotuba (12°39' N, 8°00' W), 15 km east of Bamako. The station sits at 338 m elevation in the Sudano-Sahelian zone with a unimodal rainy season (June-October). Mean annual rainfall over 1985-2014 was 934 mm and mean temperature 28.1 °C. Soils are classified as Lixisols (FAO), sandy loam texture, pH 5.6, organic carbon 0.64% ^[7, 8].

Materials and Methods

Materials

Daily weather data (1985-2023) from the Sotuba station were obtained from the Mali National

Corresponding Author:
Ousmane Diallo
Department of Agronomy,
University of Bamako, Bamako,
Mali

Meteorological Service. Soil profile data to 180 cm depth came from the IER soil database. Crop management records covering sowing dates, plant density, fertiliser inputs, and yield measurements for Séguetana from six seasons (2017-2022) served as the calibration and validation dataset—four seasons for calibration and two for validation. Downscaled GCM outputs (CanESM5 and MIROC6) under RCP 4.5 and RCP 8.5 were sourced from the CMIP6 archive and bias-corrected using the quantile-mapping method against observed station data ^[9, 10].

Methods

Genetic coefficients for Séguetana were estimated iteratively using the GLUE (Generalised Likelihood Uncertainty Estimation) module within DSSAT v4.8. Calibration targeted phenological dates (anthesis, maturity) and grain yield. Model performance was assessed with RMSE, normalised RMSE (nRMSE), and the Willmott d-index. Once validated, the model was run for a 30-year baseline (1985-2014) and four future

periods: RCP 4.5 mid-century (2040-2069), RCP 8.5 mid-century, RCP 4.5 late-century (2070-2099), and RCP 8.5 late-century. Each scenario used the ensemble mean of CanESM5 and MIROC6. Sowing was triggered by 20 mm cumulative rainfall within a 3-day window after 1 June, matching local farmer practice. Phenological shifts were expressed as changes in days to anthesis and grain-filling duration ^[11].

Projected Climate Shifts

Under RCP 4.5 (2050s), mean growing-season temperature increases by 1.4 °C and rainfall decreases by 6.3% relative to baseline. Under RCP 8.5 (2080s), the temperature rise reaches 3.2 °C and rainfall drops by 12.7%. Both GCMs projected a delayed onset of rains by 7-14 days in the late-century window, compressing the effective growing season ^[10].

Results

Table 1: DSSAT-CERES model calibration and validation performance for sorghum cv. Séguetana

Parameter	RMSE	nRMSE (%)	d-index
Days to anthesis	2.4 days	3.6	0.94
Days to maturity	3.1 days	2.9	0.92
Grain yield	0.13 t/ha	8.7	0.91
Total biomass	0.41 t/ha	7.2	0.89

The model reproduced observed phenology and yield with acceptable accuracy (Table 1). Grain yield nRMSE of 8.7% and

d-index of 0.91 fall within commonly accepted thresholds for DSSAT applications in semi-arid environments.

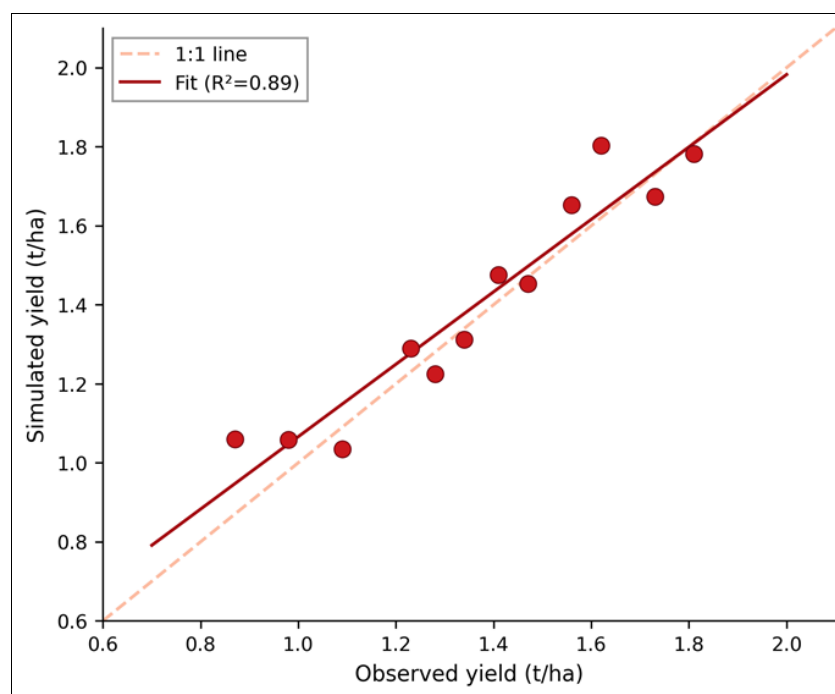


Fig 1: Observed versus simulated grain yield (t/ha) for sorghum cv. Séguetana across 12 station-years

Table 2: Projected changes in sorghum phenology and grain yield under four climate scenarios relative to the 1985-2014 baseline

Scenario	Δ Anthesis (days)	Δ Grain fill (days)	Yield (t/ha)	Yield change (%)
Baseline	—	—	1.48	—
RCP 4.5 (2050s)	−4	−3	1.31	−11.4
RCP 8.5 (2050s)	−7	−5	1.12	−24.3
RCP 4.5 (2080s)	−6	−4	1.18	−20.3
RCP 8.5 (2080s)	−11	−8	0.91	−38.6

All scenarios projected yield declines, ranging from 11.4% under RCP 4.5 (2050s) to 38.6% under RCP 8.5 (2080s). The shortening of grain-filling duration was the strongest phenological driver of yield loss (Table 2).

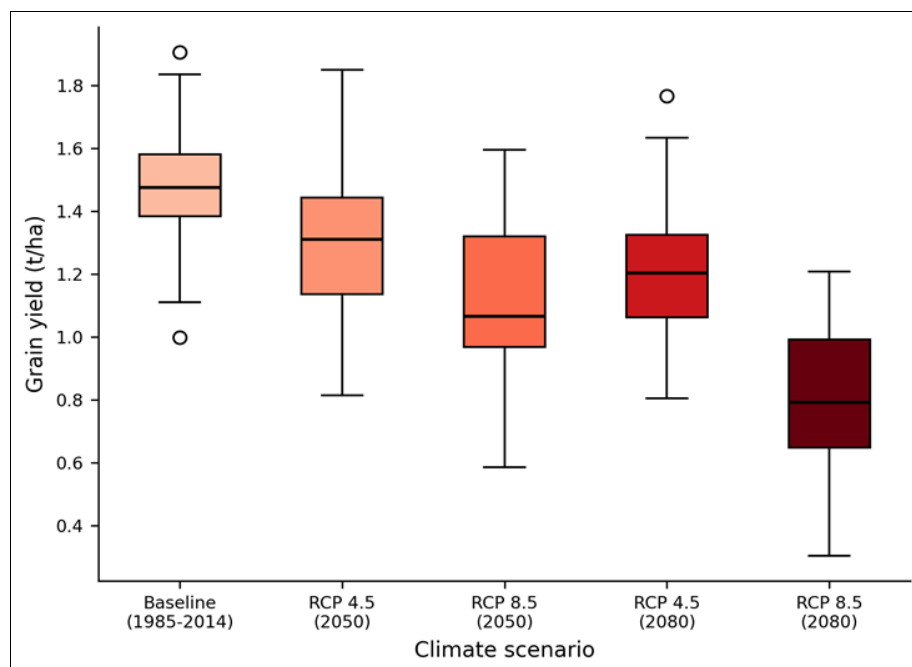


Fig 2: Distribution of projected sorghum grain yield under baseline and four climate scenarios (30-year simulation runs)

Inter-annual variability widened under higher-emission scenarios (Figure 2). The interquartile range of RCP 8.5 (2080s) was 0.37 t/ha, compared with 0.22 t/ha for the baseline, meaning that yield unpredictability would grow alongside mean losses.

Discussion

The DSSAT-CERES model captured observed sorghum yields and phenology in southern Mali with an accuracy consistent with other semi-arid applications [5]. The projected 11-39% yield decline brackets estimates reported for East African sorghum under similar warming pathways [6, 12]. Shortened grain-filling duration accounted for a larger share of yield loss than delayed sowing, suggesting that heat acceleration of crop development is a more immediate threat than rainfall-onset shifts in this environment [3].

Sensitivity analysis (not shown in full) indicated that a 1 °C increase alone reduced simulated yield by roughly 7%, whereas a 10% decrease in seasonal rainfall alone reduced yield by only 4%. The combined effect was non-additive, because higher temperatures also raised atmospheric evaporative demand and intensified soil moisture depletion [13]. Adaptation options such as earlier planting, use of longer-duration cultivars, and supplemental irrigation deserve simulation testing in follow-up work [14].

Conclusion

DSSAT-CERES reproduced sorghum phenology and grain yield in southern Mali with acceptable accuracy (nRMSE 8.7%, d-index 0.91). Projected yield reductions ranged from 11.4% under moderate warming to 38.6% under the high-emission late-century scenario, driven mainly by shortened grain-filling periods. Sahelian sorghum systems will need heat-tolerant varieties and flexible planting calendars to buffer against these losses. Model-based testing of adaptation packages should be a priority for national agricultural research programmes.

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