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Simulating pearl millet growth and yield with DSSAT-CERES-millet model: Evaluating climate-smart practices for uptake across diverse environments in Senegal

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Abstract

Background: Evaluating crop suitability across diverse agro-climatic zones is crucial for mitigating risks to agricultural yield under climate change, particularly for pearl millet production in Senegal. To facilitate informed tactical or strategic decision making, aimed at enhancing productivity, a modeling approach is essential for comprehending climate impacts and formulating effective adaptation strategies. *Methods:* The DSSAT model's capability to simulate four pearl millet cultivars (Souna-3, SL 28, SL 423, Thialack-2) under varying plant populations and micro-dosing fertilization strategies in diverse environments is evaluated in this study. The research also examines the risk associated with management practices on millet productivity in the context of climate variability and changing conditions for the period 1990–2020. To achieve these objectives, the CERES-millet model was calibrated using field data from 2022 to 2023 growing seasons for the four cultivars and subsequently validated with independent datasets from on-farm demonstrations in Senegal under various organo-mineral fertilizer applications for the same seasons. *Results:* The CERES-Millet model demonstrated high accuracy, simulating key growth stages and yield components across various millet cultivars and environments. For anthesis and physiological maturity, the model achieved low RMSE values (3–5 days and 2–4 days) and acceptable d-index ranges (from 0.6 to 0.9), indicating reliable predictions of these critical developmental milestones. The model's performance extended to accurately simulating leaf area index (LAI), grain yield, and above-ground biomass, with specific RMSE values reported for different cultivars such as Souna 3 (RMSE of 443 kg ha^{-1} for grain yield and 747 kg ha^{-1} for AGB), Thialack-2 estimated RMSE of 389 kg ha^{-1} for grain yield and 208 kg ha^{-1} for AGB. SL 28 recorded RMSE of 257 kg ha^{-1} for grain yield and 560 kg ha^{-1} for AGB, while SL 423 had RMSE of 698 kg ha^{-1} for grain and 640 kg ha^{-1} for AGB. A long-term 31-year seasonal simulation revealed that dual-purpose varieties consistently outperformed Souna 3 in terms of yield, despite significant inter-annual variability. *Conclusion:* Combining these varieties with micro-dosing fertilizer applications led to higher yield thresholds. Notably, micro-dosing fertilizer level 3 (3g/hill of NPK, 2g/hill of Urea, and 50g/hill of cow manure) demonstrated consistent stability, making it a cost-effective approach to mitigate yield variability in semi-arid regions of Senegal. Long-term simulations highlighted the promising potential of combining dual-purpose varieties with optimized micro-dosing strategies to enhance yield stability and resilience. This approach offers a practical method for mitigating the effects of climate variability in Senegal and similar environmental contexts.

Keywords: CERES-Millet model, modeling, climate variability, and change, probability of exceedance, optimum conditions

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Introduction

Ensuring household food security remains a central challenge for household farming systems in sub-Saharan Africa, where smallholder farmers are particularly vulnerable to climate variability (Falconnier *et al*., 2018; Lalou *et al*., 2019). Addressing this challenge requires more rigorous monitoring and evaluation of different climate action projects and investments, as well as the adoption of climate-smart practices since rain-fed agriculture systems are becoming more vulnerable to the impacts of climate change (Perez *et al*., 2015).

In Senegal, millet stands out as a vital component of food and nutrition security (Faye *et al*., 2018, 2023). It serves as a staple crop grown extensively across the country (Diatta and Thomason, 2016; Faye *et al*., 2023). Known for its resilience to dry conditions and ability to maintain greenery even with minimal moisture, millet holds significant value for smallholder farmers (Uppal *et al*., 2015). Not only does it provide both feed and grain, but its suitable spacing also allows for a higher grain-fodder ratio, making it a valuable crop in agricultural practices (Pilloni *et al*., 2022; Faye *et al*., 2023). The high domestic demand for millet, whether for human consumption or livestock feed, translates into a valuable income source for numerous smallholder farmers in Senegal (Dov *et al*., 2012). Research has shown that certain varieties of millet can serve as crucial forage sources in regions like the Sahel, especially under rainfed conditions (Faye *et al*., 2023). Therefore, in areas with low productivity, pearl millet holds promise for climate-resilient agriculture, provided it is managed with enhanced agronomic practices (Uppal *et al*., 2015). A study by Sultan *et al*. (2013) demonstrated that pearl millet exhibits resilience to drought conditions and can maintain yield stability under variable climatic scenarios, highlighting its potential as a reliable staple crop in the face of climate change and contributing to sustainable agricultural practices.

The average farmer's millet yield in Senegal is between 500 and 900 kg ha^{-1}, significantly below the achievable yield potential of 3500 kg ha^{-1} (Faye *et al*., 2023). This yield gap can largely be attributed to two key challenges such as the high costs of fertilizers, which are often unaffordable for smallholder farmers (IFDC, 2016), and suboptimal planting practices, including low plant density. Financial constraints prevent many farmers from fully utilizing fertilizers, which could otherwise boost yields. Similarly, farmers' sowing practices, typically involving a low density of 12,500 hills per hectare in monoculture, contribute to low yields, limiting their ability to access the benefits of improved varieties and optimal growth conditions (Adiku *et al*., 2015; Faye *et al*., 2023). Research by Pilloni *et al*. (2022) and Faye *et al*. (2023) suggests that increasing planting density to an optimal 25,000 hills per hectare can enhance both grain and fodder yields, but densities beyond this threshold lead to negative effects due to increased competition for nutrients, water, and light. Together, fertilizer affordability and plant density underscore the importance of developing strategies that optimize both factors for improved agricultural productivity. Integrated soil fertility management (ISFM), particularly micro-dosing, offers a promising solution by enhancing crop productivity, boosting farmers' incomes, and mitigating environmental risks (Akinseye *et al*., 2023a). Addressing these challenges through tailored fertilizer application and optimal plant density can significantly enhance yields and contribute to the resilience of smallholder farmers. Climate change predictions for West Africa, including Senegal, suggest a concerning outlook. Projections indicate a significant decrease in rainfall, coupled with a uniform increase in minimum and maximum temperatures during the growing season (Adiku *et al*., 2015; Almazroui *et al*., 2020). These changes seriously threaten the livelihoods of subsistence farmers and rainfed crop production systems (Sultan *et al*., 2023; Zagre *et al*., 2024). Moreover, the region experiences a rise in climate disasters like droughts and floods, further complicating the situation for impoverished farmers (Salack *et al*., 2011). Understanding the complex spatial variability in farming landscapes across sub-Saharan Africa is essential for developing effective solutions to combat climate change impacts. Given the region's challenges, including low soil fertility, erratic rainfall patterns, and low inputs used by farmers, adopting resilient farming practices becomes imperative for the sustainability of agricultural livelihoods (Perez *et al*., 2015).

Models assessing farm-level yields under different fertilizer strategies and rainfall gradients have proven their efficacy, aiding in decision making for farmers (Dodds, 2010; Sultan *et al*., 2019). Thus, climate and agricultural modeling tools play a vital role in evaluating the impacts of climate change and assisting stakeholders in making decisions to mitigate its adverse effects (Lobell and Burke, 2010; Araya *et al*., 2015; Jägermeyr *et al*., 2021). These tools provide valuable insights for enhancing crop forecasting, developing climate variability indices, and even supporting agricultural insurance programs (Koo *et al*., 2016). Thereby, the use of Decision Support Systems for Agricultural Technology (DSSAT) has demonstrated its effectiveness in simulating crop growth and development in arid and semi-arid zones, especially when considering the combined effects of weather uncertainties, fertilization strategies, and optimum sowing windows on yield and profitability (MacCarthy *et al*., 2010; Akinseye *et al*., 2017; Tovihoudji *et al*., 2019). DSSAT has the ability to simulate crop growth and development in the conditions of semi-arid zones either for a single cropping or intercropping system (Jones *et al*., 2003). Rotation makes it more suitable for use in West African farming systems. Various studies have validated the accuracy of these models, underscoring their utility in optimizing agricultural practices and mitigating climate risks.

For example, Adiku *et al*. (2015) reported that the DSSAT model adequately simulated the maize, millet, and peanut on a farm scale in the semi-arid areas of Ghana and Senegal. Furthermore, in a semi-arid region of Ghana, MacCarthy *et al*. (2010) highlighted the effectiveness of the DSSAT model to simulate the nutrient and water productivity of sorghum in smallholder farming systems. Adam *et al*. (2020) similarly used the DSSAT model for a multiple-farm assessment of the effect of future climates on sorghum grain yield in response to fertilizer rate and plant density in Mali and Ghana. Similarly, Ullah *et al*. (2019) successfully calibrated and evaluated CERES-Millet in Pakistan to measure climate change and its effects on pearl millet in arid and semi-arid climate conditions. Soler *et al*. (2008) used a modeling approach that accurately simulate growth, development, and yield for millet grown in two contrasting environments and under different management practices, including multiple genotypes and different nitrogen fertilizer application rates, to establish the optimum planting dates for pearl millet in Niger. Araya *et al*. (2022) demonstrated that the DSSAT model effectively simulated sorghum and millet yields in Senegal, highlighting suitable crop management strategies to mitigate climate risks by midcentury.

Toure *et al*. (2018) reported that DSSAT adequately simulated the yield of two millet varieties in two agroecological zones of Mali under different climate change scenarios. The above examples highlight the importance of this study which aims to (i) assess the potential of the DSSAT model to simulate the response of pearl millet varieties to plant populations and fertilization strategies on millet productivity, and (ii) determine the optimal yield under various microdose fertilizer strategies across different rainfall gradients at farm scale under changing climatic conditions. Unlike conventional fertilization practices, only a few studies have so far attempted to model crop response to fertilizer considering micro-dosing techniques (Tovihoudji *et al*., 2019). Thus, this study will contribute to implementing climate-smart agriculture practices, improving resource efficiency, and enhancing the resilience of agri-food systems, essential steps toward achieving sustainable development goals in sub-Saharan Africa and beyond.

Methods

STUDY AREA

The study was conducted at five locations in Senegal in four Agroecological zones (AEZ) (Fig. 1): Meouane (15°3′59.76″N,

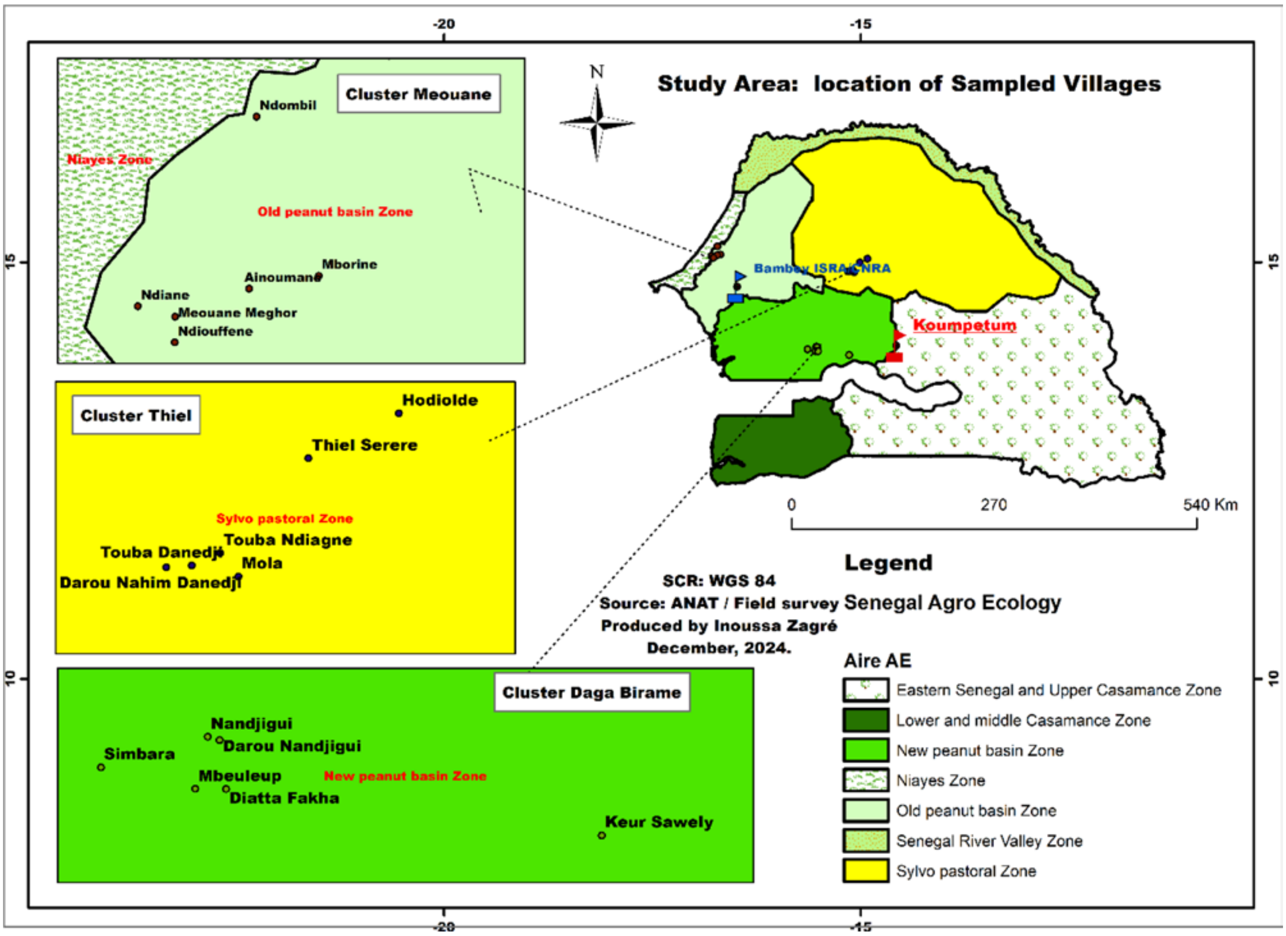

Fig. 1. Study area map showing the location of sampled villages.

16°45′26.28″ W) and Bambey research station of ISRA/CNRA (14°42′31.32″N, 16°28′47.28″W) located in Old Peanut Basin. Daga Birame (13°56′39.84″N, 15°30′47.88″W) is located in New Peanut Basin while, Thiel (14°52′12.00″N, 15°5′0.24″W) and Koumpetum (14°0′6.48″N, 14°34′21″ W) are respectively in Sylvopastoral Zone and Eastern and Upper Casamance Zone (Fig. 1). All these sites are located in the semi-arid zone of Senegal, characterized by Sahelo-Sudanian and Soudanian-Guinean climate conditions (Joseph *et al*., 2023; Zagre *et al*., 2024). These areas exhibit high variability in annual rainfall (Araya *et al*., 2022; Joseph *et al*., 2023). According to Zagre *et al*. (2024), Meouane receives at least 350 mm of rainfall annually in a good year and less than 300 mm in a below-average year. In Thiel, the annual average rainfall ranges between 300 and 500 mm, while in Daga Birame, it ranges between 400 and 600 mm. Bambey experiences a mean annual temperature of 27−28°C and an average yearly rainfall of about 520 mm (Faye *et al*., 2023). The average annual rainfall in Koumpetum (Tambacounda region) ranged between 400 and 800 mm from 1990 to 2020. The soils in these zones are predominantly sandy with low fertility and seasonally waterlogged or flooded clays, commonly referred to as *Dior soils* (FAO, 1993; Faye *et al*., 2023).

DATA COLLECTION

Experiments design and crop management

The data collection in this study followed the participatory research and extension approach (PREA) which is expected to accelerate the adoption of CSA package dissemination toward climate risk management (Ajeigbe and Dashiell, 2010). For model calibration with DSSAT CERES-Millet, multi-locations trials were established under optimum conditions across four contrasting environments in Meouane and Daga Birame during the 2022 and 2023 cropping seasons and in Bambey research station ISRA/CNRA and Koumpetum for 2023 cropping season. The experiments were laid out in a randomized complete block design (RCBD) with three replications and two factors (variety and plant density). Thus, in each site three dual-purpose (Thialack 2, SL 28, and SL 423) and farmers' common variety (Souna 3) were assessed in two population densities (12,500 hills/ha and 25,000 hills/ha) under recommended mineral fertilizer rates in Senegal (150kg of NPK 15-15-15 and 100 kg of urea). This trial was designed to assess the adaptability of dual-purpose millet varieties along the rainfall gradient to improve resilience to climate variability and promote sustainable farming practices. The plots contained 5 rows, sown within a row at 0.9 m for low density and 0.45 m for high density. The plot size was 5 m long and 4.5 m wide. The space between the rows was 0.9 m and the block size was 22.5 m^2 (5 × 4.5 m). The space between the sub-plot was 1 m, the block was 1.8 m, and the plot size was 799.8 m^2.

Furthermore, for model validation, we used data collected through on-farm participatory demonstration trials established across the three selected clusters (Thiel, Meouane, and Daga Birame) during the growing seasons of 2022 and 2023. The AICCRA project (Accelerating Impacts of CGIAR Climate Research for Africa) implemented multi-location demonstration plots in Senegal to assess how different climate risks affect pearl millet varieties and farm management practices. This initiative aimed to demonstrate the benefits of climate-smart management practices and the use of decision-support tools (DSTs) for seasonal yield forecasting. A total of 18 villages were selected across the three clusters. In each cluster, six villages were associated, and, in each village, four farmers were selected for implemented technology using an Integrated Soil Fertilizer Management (ISFM) such as a micro-dosing strategy to produce pearl millet given a total of 72 demonstration plots established during each season. The details of all these villages and their coordinates can be found in the supplementary materials. The demonstration plots design had four micro-dosing fertilizer treatments and two millet varieties, farmers within the same village were used as replications, and each sub-plot size was 63 m^2 (10 × 6.3 m) with 7 rows, sown at 0.45 m within a row. The varieties evaluated at the Thiel cluster were Souna 3, and Thialck-2, the Meouane cluster was Souna-3, and SL 423 while the Daga Birame cluster was Souna-3, and SL 28. SL 28, SL 423, and Thialack 2 are dual-purpose varieties with medium to short-duration cycles while Souna 3 is an improved local variety with a short-duration (ISRA, 2014; Gueye *et al*., 2015). The characteristics of the genetic materials are contrasted from one to another. The fertilizers treatments used were: F1-150kg of NPK (15:15:15) + 100kg of urea(46%N), F2-150kg/ha (NPK)+ 100kg/ha (Urea) + 2.5ton/ha cow manure, F3-75kg/ha(NPK)+ 50kg/ha (Urea) +1.25ton/ha cow manure, F4-75kg/ha(NPK) + 2.5 ton/ha (cow manure). The planting dates for pearl millet varied across the different clusters of demonstration plots, and information was collected for each plot. Furthermore, for long-term seasonal simulation, rainfall onset was determined for each cluster using the definition given by Sivakumar (1988) and widely used by previous studies in the Sahelian zone (Akinseye *et al*., 2016; Joseph *et al*., 2023; Zagre *et al*., 2024). Based on these treatments, the quantity of fertilizer per hill was derived. This implies that F1-6g/hill of NPK + 4g/hill of urea, F2-6g/hill of NPK+ 4g/hill of urea+100g/hill of cow manure, F3-3g/hill of NPK + 2g/hill of urea + 50g/hill of cow manure, and F4-3g/hill of NPK + 100g/hill of cow manure. These micro-dosing rates are also raised by previous studies (Tabo *et al*., 2007; Akinseye *et al*., 2023a). The laboratory analysis of cow manure used for organic amendment in this study gives a detail of 24.3% organic carbon, 0.37% nitrogen, 0.41% phosphorus, and 0.44% potassium.

Crop data collection and measurements

For the experimental trial, different data were collected including crop phenology (date to anthesis, and physiological maturity), leaf number, leaf area index (LAI), biomass time series, grain, and aboveground biomass (AGB) yield at harvest. Anthesis and physiological maturity dates were determined using plants in the three middle rows of each plot. Regarding the morphology parameters such as leaf number and LAI, they were measured from 3 weeks after planting to 9 weeks with intervals of 2 weeks between each measurement. LAI was measured using the DELTA PAR/LAI sensor. Concerning farmers' demonstration plots, grain and AGB at harvest were measured. Millet panicles and fodder were harvested at physiological maturity from the three central lines of each plot (7.29 m^2) to avoid border effects. Stover weight was taken after sun drying for 14 days when almost no change in weight was observed between consecutive measurements (Reddy *et al*., 2010). The yield was extrapolated and then reported on a hectare basis. The panicles were threshed and weighed to determine grain yield. The grain and stover yields from each plot were estimated in kg ha^{-1}.

Soil input data

Each year, before sowing, soil samples were collected at various depths (0–15 cm, 15–30 cm, and 30–60 cm) for experimental trials and in each village for on-farm demonstration plots. Soil samples were analyzed at the ICRISAT soil analysis laboratory at Sadore, Niger for physical-chemical properties namely bulk density (g/cm^3), sand (%), silt (%), clay (%), pH/H_2O (1:2.5), OC (%), N (%), P (mg/kg), K (%), and CEC (cmol$^+$/kg) (Table 1). The soil profile information is key in the cropping modeling system for running the simulation (Tsuji *et al*., 1994), additional data of two layers (60–100 and 100–200 cm) were downscaled with the corresponding farm's reference coordinates of each location from SoilGrids1km at 10-km resolution using the approach given by Han *et al*. (2019). The analysis emphasized that the soil across the locations was mainly sandy loam in texture with a low percentage of organic carbon and nitrogen. The sand content ranges from 65 to 87.2% across all the sites surveyed in this study (Table 1). The bulk density, silt content, and clay content range respectively from 1.42 to 1.58 g/cm^3, 5.2 to 23.8%, and 8.2 to 13.3%. The soil was moderately acidic to slightly acidic to neutral pH across the locations (Table 1). Furthermore, the fertility determinant (SLPF) factor was manually adjusted for each location based on the initial set of cultivar coefficients. As input, measured soil physical-chemical properties mentioned above were used. Soil hydrological properties such as soil water content at field capacity (drained upper limit = DUL), at permanent wilting point (lower limit = LL), and saturation (SAT) were parameterized from SoilBuild following the approach given by Ritchie (1981) and Gijsman *et al*. (2002).

Weather conditions in the study area

Weather files for 2022 and 2023 were created using daily minimum and maximum air temperatures, rainfall, and solar radiation recorded at the experimental site and plotted using the WeatherMan utility program in DSSAT (Pickering *et al*., 1994). In each community, manual and automatic rain gauges were established for rainfall data collection during the growing seasons of 2022 and 2023. Regarding the long-term weather data, the approach used in a previous study (Araya *et al*., 2022; Akinseye *et al*., 2023b) in the Sahel zone was done to generate daily rainfall at a 4.9 km resolution for 31 years (1990–2020) using the downscaled Climate Hazards Group InfraRed Precipitation with Station (CHIRPS). Furthermore, daily minimum and maximum temperature and solar radiation were downloaded from the database for Climatology Resource for Agroclimatology, National Aeronautics and Space Administration (NASA) (Available at: http://power.larc.nasa.gov, assessed 18 March 2024) for the corresponding location reference coordinates. Thereby, the approach with R scripts was used to merge rainfall data from CHIRPS with NASAPower data (Akinseye *et al*., 2023b; Garba *et al*., 2024). Figure 2A–D represents the long-term weather information and the two years growing seasons (2022, 2023) to capture the variability across the clusters. The results showed a moderate to high variability of 14, 18, and 24% in the Thiel, Daga Birame, and Meoaune clusters respectively (Zagre *et al*., 2024). Relative differences in total rainfall amounts were observed among the three clusters. The mean annual rainfall of the growing season 2022 and 2023 is greater than the historical period (1990–2020) for all the locations. Over the 31 years, the mean rainfall received by Daga Birame was 649 mm while it was 497 mm and 399 mm, respectively in Thiel and Meouane. There was generally a strong negative correlation coefficient (r = 0.83) between the onset and length of the growing season across the sites (Fig. 2D). The average minimum and maximum temperatures over the 31 years were 21 and 35°C for Daga Birame, 21 and 32°C for Meoaune while in Thiel it was 22 and 36°C.

CERES-MILLET MODEL DESCRIPTION AND CALIBRATION PROCEDURE

The CSM-CERES-millet model of the DSSAT Version 4.8 (Hoogenboom *et al*., 2019) was selected for a system analysis approach. The model simulates crop growth, development, and yield by capturing both vegetative and reproductive processes, as well as the dynamics of water, nitrogen, and carbon in the soil, and weather and cultivar traits. Ritchie *et al*. (1998) and Jones *et al*. (2003) provide detailed explanations of these processes. To accurately simulate the growth and yield of a pearl millet cultivar, the model requires specific crop and cultivar parameters, also known as genetic coefficients (GCs). Additionally, it incorporates a thermal time calculation similar to growing degree days, which considers the optimal temperature range where plant development rates increase linearly with rising temperatures. Thereby, the Priestley and Taylor method for evapotranspiration was applied in this study.

Table 1. Physical and chemical properties used for model parameterization and evaluation in each cluster.

Site	Profile Depth (cm)	BD (g/cm3)	OC (%)	Sand (%)	Silt (%)	Clay (%)	pH/H2O	N (%)	Phosphorus (mg/kg)	Potassium (%)	CEC-AgTu ($cmol^+/kg$)
Experimental trials used for model calibration											
Daga Birame	0–200	1.52	0.18	71.7	17.3	11.1	5.6	0.015	44.3	0.05	4.57
Meouane	0–200	1.43	0.30	84.2	6.2	9.7	6.3	0.025	88.4	0.05	3.41
Koumpetum	0–150	1.42	0.15	82.3	10.3	10.4	6.0	0.013	92.3	0.10	5.23
Bambey (ISRA/CNRA)	0–150	1.51	0.05	81.3	9.3	9.2	6.2	0.005	90.4	0.05	3.73
Daga Birame cluster											
Diatta Fakha	0–200	1.52	0.12	77.6	14.3	8.2	5.8	0.012	78.3	0.08	3.91
Keur Sawely	0–200	1.52	0.19	70.9	16.5	12.7	5.7	0.020	111.6	0.14	5.33
Mbeuleup	0–200	1.50	0.19	65.7	23.5	10.8	5.9	0.016	82.4	0.11	3.84
Nandjigui	0–200	1.50	0.15	76.5	10.3	13.3	5.9	0.017	89.3	0.10	3.64
Ngouye	0–200	1.51	0.15	65.0	23.8	11.3	5.9	0.016	33.9	0.12	4.95
Meouane cluster											
Ainomane	0–200	1.51	0.06	85.4	6.5	8.2	6.1	0.007	46.1	0.05	4.59
Ndombil	0–200	1.46	0.08	87.2	5.2	7.7	6.2	0.011	90.6	0.06	3.60
Ndiane	0–200	1.58	0.12	78.1	9.7	12.3	5.8	0.014	154.6	0.04	3.92
Ndiouffene	0–200	1.43	0.07	78.5	14.0	7.6	6.2	0.008	89.7	0.05	3.41
Mborine	0–200	1.58	0.09	77.0	10.1	13.0	5.9	0.009	91.8	0.06	4.47
Thiel cluster											
Touba Ndiagne	0–200	1.42	0.15	80.8	9.5	10.0	6.9	0.015	75.3	0.07	7.04
Mola	0–200	1.42	0.10	78.8	11.0	10.5	6.6	0.012	77.5	0.10	3.53
Touba Danedji	0–200	1.42	0.11	82.3	9.1	9.0	6.6	0.012	70.8	0.06	4.23
Darou Naim	0–200	1.42	0.13	82.1	9.0	9.2	6.7	0.012	65.7	0.07	4.57
Thiel Serere	0–200	1.42	0.10	81.1	9.8	9.4	6.8	0.012	79.6	0.10	5.39
Hondiolde 3	0–200	1.42	0.09	72.7	18.8	8.7	6.6	0.011	82.4	0.11	5.06

BD = bulk density, OC = organic carboncontent, N = Nitrogen (%), and CEC = cation exchange capacity.

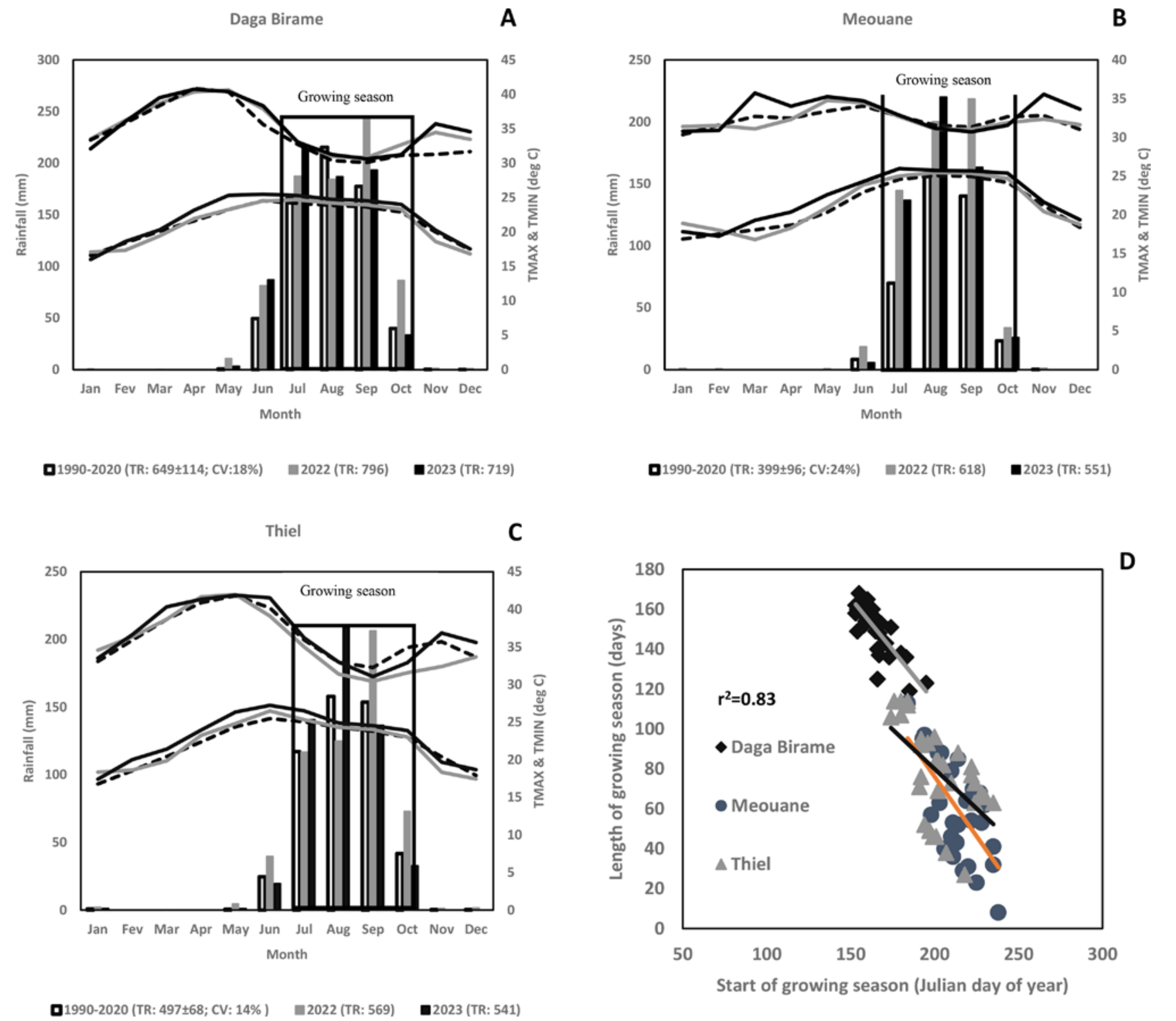

Fig. 2. (A–D) Cumulative monthly rainfall and temperature over 31 years (1990–2020) for Daga Birame (A), Meaoune (B), Thiel (C), and start and length of growing (D). TR = total rainfall, and CV = coefficient of variation.

Furthermore, radiation efficiency for millet photosynthesis was considered as described by Jones *et al*. (2003), and the CENTURY method was used to simulate soil carbon and nitrogen dynamics (Gijsman *et al*., 2002). To ensure the model's accuracy and reliability for the specific conditions of this study, a thorough calibration process was undertaken. The model was calibrated with optimum treatment (recommended rate of mineral fertilization including micro-dosing strategy) under two plant populations (12,500 hills/ha and 25,000 hills/ha) for pearl millet three dual-purpose varieties (Thialack 2, SL 28, SL 423) and one farmers' improved local variety (Souna 3) in four contrasting environments namely Meaoune, and Daga Birame during the years 2022 and 2023 and Bambey station research of ISRA/CNRA, and Koumpetum for 2023 cropping season. The approach of multilocation trials for model calibration has already been used by Beah *et al*. (2021), Weitkamp *et al*. (2023), Kamara *et al*. (2023), and Akinseye *et al*. (2023b). It strengthens the model's predictive capabilities, offering valuable insights into millet production across a broader range of environments. The genetic coefficient was estimated during model calibration using field data on phenology, growth, grain, and AGB yields. The best value for each phenological and development coefficient was chosen using an iterative process (Nissanka *et al*., 2015; Garba *et al*., 2024). The model's performance was assessed using anthesis, maturity dates, growth, and yield. This approach was done following a sequential order, starting with the phenological development coefficients and progressing to the crop growth and yield coefficients (Bowen *et al*., 1998). Since the millet cultivars used in the experiment had not been previously modeled with DSSAT, the genetic coefficients were calibrated by choosing an early-maturing cultivar from Niger (Zatib) calibrated by Akponipke (2008) as a reference. The combination of coefficients that resulted in the smallest root mean square error (RMSE) and the highest coefficient agreement (d-index) between observed and simulated values were selected as the final cultivar coefficients. Table 2 displays the adjusted genetic coefficient for each variety. Initially, the phenology-controlling coefficients (P1, P20, P2R, P5, and PHINT) were adjusted to correspond with the dates of anthesis and maturity as well as the number of leaves. Afterward, to reduce the RMSE between the simulated and measured LAI, biomass, and yield, the G1, G4, G5, and GT parameters were changed (Jones *et al*., 2003). After modifying the species-specific parameters, the soil fertility factor (SLPF) was modified. After manual modification, the error between the simulated and observed total biomass was minimized, and the value was set at 0.75.

Table 2. Effect of the fertilization strategies and variety type on grain and stover yields (kg ha^{-1}) of pearl millet varieties in Daga Birame, Meouane, and Thiel clusters respectively.

	Gain yield			AGB		
Factor	**Daga Birame**	**Meouane**	**Thiel**	**Daga Birame**	**Meouane**	**Thiel**
Variety type (VT)						
Improved local	1800	1450	1265	7338	6332	6024
Dual-purpose	1941	1646	1501	7595	6852	6351
LSD (*P*-value)	282.3^{ns}	195.6^{*}	224.4^{*}	235.1^{ns}	210.2^{***}	552.5^{ns}
CV (%)	37.7	41.8	28.5	12.5	13.6	33.5
Fertilizer (F)						
F1	1951	1690	1532	7655	6866	6444
F2	2254	2041	1600	8238	7632	6918
F3	1653	1314	1340	7091	6152	5922
F4	1424	1158	1148	6687	5737	5565
LSD (*P*-value)	326.9^{***}	240.1^{***}	305.5^{*}	307.2^{***}	258.2^{**}	767.2^{ns}
CV (%)	35.2	38	31.1	11.3	11.8	33.9

ns, *, **, and *** indicate that the source of variation was significant at $P < 0.05$, 0.01, and 0.001, respectively. F1 = 150 kg/ha (NPK15:15:15) + 100 kg/ha (urea 46%N); F2 = 2.5 tons/ha (cow manure) + 150 kg/ha (NPK15:15:15) + 100 kg/ha (urea 46%N); F3 = 1.25 tons/ha (cow manure) + 75 kg/ha (NPK15:15:15) + 50 kg/ha (urea 46%N); F4 = 2.5 tons/ha (cow manure) + 75 kg/ha (NPK15:15:15); SED, standard errors of differences of mean; CV (%), coefficient of variations in percent, LSD, least significant difference, AGB, aboveground biomass.

CERES-MILLET MODEL EVALUATION

To appreciate the model's accuracy, the calibrated model was evaluated using final grain and AGB yield of independent data from on-farm demonstration plots in each cluster (Meouane, Daga Birame, and Thiel) of the 2022 and 2023 growing seasons. The accuracy of model simulations was assessed based on the MBE, RMSE, normalized RMSE (nRMSE), and coefficient of agreement (d-index) (Willmot Cort, 1982; Bélanger, 2000). The simulations in each cluster were performed across 24 selected farmers for each year (2022 and 2023). To reduce the heterogeneity from one on-farm demonstration plot to another, the data of the four farmers in the same village were averaged in each cropping season. The model was thereby set accordingly to align with this approach. Daga Birame cluster was concerned by Souna 3 and SL 28, Meaoune, Souna 3 and SL 423 while Thiel was Souna 3 and Thialack 2. The soil survey across the community indicated a very low fertility class which implies the adjustment of SLPF to minimize the error between the observed and simulated total biomass ranked between 0.45 to 0.75 in Daga Birame, 0.41 to 0.65 in Thiel, and 0.53 to 0.6 in Meouane cluster. The accuracy and reliability of the model were assessed by calculating the statistical indices between observed and simulated values. Statistical indices are shown in Eqs. (1)–(4).

$$MBE = \frac{1}{N}\sum_{i=1}^{n}\left(O_i - S_i\right) \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{N}} \tag{2}$$

$$nRMSE = \left[\frac{RMSE}{\bar{o}}\right]\times 100 \tag{3}$$

$$d-index = 1 - \frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{\sum_{i=1}^{n}\left(\left|S_i - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)^2} \tag{4}$$

Where S_i is the simulated values, O_i is the observed values and n is the number of observations. The simulation is considered excellent with a normalized RMSE less than 10%, good if the nRMSE is greater than 10 and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30% (Loague and Green, 1991).

MODEL APPLICATION: EFFECT OF POPULATION DENSITY AND FERTILIZATION STRATEGIES USING MICRO-DOSING TECHNIQUES

A simulation of long-term seasonal analysis was performed for the period 1990–2020 after the successful model calibration and evaluation of the four pearl millet cultivars across contrasting environments. This seasonal simulation was set based on the on-farm trial carried out during the growing seasons of 2022 and 2023. Following the same approach, in each cluster, one dual-purpose variety among the three used above for model evaluation (SL 28, SL 423, and Thialack 2) was simulated compared to farmers' common variety (Souna 3). This was to assess the risk of climate variability on the grain yield and to identify the optimum micro-dosing fertilizer strategy for farmers vis-à-vis farmers' practices in each rainfall gradient. Based on the definition of rainy season onset in the Sahel given by Sivakumar (1988) and confirmed to be suitable for this zone (Akinseye *et al*., 2016; Joseph *et al*., 2023). The model's initial water, nitrogen, and organic matter contents were set at the beginning of each simulation (1 May). This allows the elimination of the residual effect of these parameters in the soil profile on crop growth and development for the current season (Beah *et al*., 2021). Analysis of the onset and the cessation of the rainy season across the clusters (Zagre *et al*., 2024) allows for setting the optimum planting window from June 26 to July 25 which covers all the clusters. Four organo-mineral micro-dosing techniques were used to determine the optimum N application rate for each cluster. The simulation was set at two planting densities (12,500 hills/ha and 25,000 hills/ha). The application procedure for on-farm demonstration plots by farmers was applied in the long-term seasonal simulation. The cow manure rates were applied at the sowing. NPK rates were applied 2 weeks after planting while urea rates were applied 3 weeks after NPK application.

DATA ANALYSIS

R software version 4.3.3 was used for statistical analysis of long-term simulation yield. Two-way ANOVA was performed to assess fertilizer and density effects on grain yield. The Tukey test at $p < 0.05$ was used for mean discrimination. Furthermore, to assess adaptability, the means, and coefficient of variation (CV) were computed. Also to assess risk, the probability of exceedance was calculated to determine the likelihood that grain yield in any given year will exceed the given threshold value.

Results

EFFECT OF FERTILIZATION STRATEGY AND MILLET VARIETIES ON YIELD PERFORMANCE IN THREE CLUSTERS

The evaluation of ISFM and dual-purpose varieties as climate-smart technologies at the farm scale showed a significant ($p < 0.05$) effect on grain yield compared to the farmer-improved local variety in the Meouane and Thiel clusters, except in Daga Birame (Table 2). Dual-purpose varieties outperformed farmer-improved local variety in all the clusters where grain yield increased by 37% in Thiel, 15% in Meouane, and 8% in Daga Birame. Regarding the AGB, a significant effect was observed only in Meouane. The effect of micro-dosing fertilizer strategies was significant on grain yield and AGB across all three clusters. The organo-mineral micro-dosing fertilizer application (F2) performed better on grain and stover yields across all the clusters. Furthermore, the results show a significant coefficient of variations (CV > 20%) between varieties and fertilizer strategies for grain yield across the three clusters (Table 2). A moderate coefficient of variations (CV < 20%) was observed for AGB in all clusters except for fertilizer in Thiel.

Characterization of four millet cultivars genotypic coefficients and yield potential

The four cultivars have been described by ISRA (2014) and CILSS (2017), Souna 3, the improved local variety is early-maturing (85–95 days), is generally photoperiod insensitive and has a yield potential from 2.4 to 3.5 t/ha; Thialak 2, the dual-purpose variety has moderate photoperiod sensitivity, medium maturity cycle (90–95 days) and a yield potential from 2 to 3t/ha; SL-423 and SL 28, the dual-purpose varieties are photoperiod insensitive, an early-maturing (85–95 days), and have yield potential from 2.5 to 3.5 t/ha. Table 3 shows the generated values for the cultivar coefficients for each variety. The genotypic coefficient P1 was 310°C day for Souna 3. SL 28 and SL 423 while it was 240°C day for Thialack 2. The P20 was 12.8 h for Souna 3. SL 28 and SL 423 while it was 11.6 h for Thialack 2. There was low variation among the P2R, P5 G1, and GT varieties while no variation was observed in G4 and G5. Therefore, the thermal time between successive leaf tip appearances (PHINT) was slightly different between the four varieties.

MODEL CALIBRATION AND EVALUATION

The model was calibrated with optimum conditions and two density levels for the pearl millet cultivars (Souna 3, SL 28, SL 423, and Thialack 2) in four contrasting environments (Meoaune, Bambey station research of ISRA/CNRA, Daga Birame and Koumpetum) during the growing seasons of 2022 and 2023. The iterative process of genetic coefficient adjustment was used to fit the simulated values close to the observed. The model globally predicted well the anthesis and physiological maturity dates across the contrasting environments for all the cultivars (Table 4). The coefficient of agreement (d-index) for anthesis ranked from 0.52 to 0.91 while it was from 0.8 to 0.86 for physiological maturity for the four cultivars across the contrasting environments. The model overestimated the anthesis date for Souna 3, SL 28, and SL 423 ranked from 2 to 3 days while underestimated for Thialack 2 of 1 day. The maturity date was overestimated for all the cultivars from 1 to 2 days. Regarding the morphological parameters, the performance of the model was appreciable. d-index was ranked between 0.62 to 0.85 and 0.75 to 0.8 for LAI and leaf number, respectively. These results indicate a satisfactory level of agreement between simulated and observed data for these key growth indicators. The yield components (AGB and grain yield) were globally well simulated for all the cultivars. The model underestimated AGB for three dual-purpose cultivars (SL 28, SL 423, and Thialack 2) while it overestimated for Souna 3. Similarly, for grain yield, the model overestimated for Souna 3 and Thialach 2 while it underestimated for SL 28 and SL 423 (Table 4). The RMSE was low for the four cultivars and ranged from 208 to 747 kg ha^{-1} for AGB and from 257 to 698 kg ha^{-1} for grain yield.

MODEL VALIDATION: PERFORMANCE USING PARTICIPATORY FARM-LEVEL DATA

After calibration, the model performance was checked with on-farm data for each cluster (Meoauen, Daga Birame, and Thiel) under high density and four levels of organo-mineral fertilizer using a

Table 3. Genetic coefficients for model calibration.

Variables	Description	Souna 3	SL 28	SL 423	Thialack 2
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 10°C) during which the plant is not responsive to changes in photoperiod	310.0	310.0	310.0	240.0
P20	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values greater than P2O, the rate of development is reduced	12.8	12.8	12.8	11.6
P2R	The extent to which phasic development leads to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O	310.0	340.0	340.0	130.0
P5	Thermal time (degree days above a base temperature of 10°C) from the beginning of grain filling (3–4 days after flowering) to physiological maturity	240.0	210.0	230.0	260.0
G1	The scaler for relative leaf size	1.4	1.2	1.0	0.7
G4	The scaler for partitioning assimilates to the panicle (head)	1.9	1.9	1.9	1.9
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances	68.0	70.0	68.0	65.0
GT	Tillering coefficient, equivalent to G1, but on tillers	1.3	1.3	1.5	1.5
G5	Potential grain size, mg	11.0	11.0	11.0	11.0

Table 4. Results of model calibration of phenological and growth parameters for the four selected varieties under contrasting environments in 2023.

Parameters/cultivars	Unit	Mean observed	Mean predicted	MBE	RMSE	d-index
Souna 3						
Anthesis	DAP	60	62	2	3	0.91
Physiological maturity	DAP	85	87	2	3	0.86
LAI-Max	m2/m2	3.5	3.43	−0.1	0.3	0.62
Leaf Number		13	13	0.3	1	0.79
AGB	kg/ha	6206	6627	421	747	0.89
Grain yield	kg/ha	2537	2541	4	443	0.69
SL 28						
Anthesis	DAP	61	64	3	4	0.60
Physiological maturity	DAP	85	87	2	4	0.80
LAI-Max	m^2/m^2	3.49	3.72	0.2	0.4	0.83
Leaf Number		13	13	1	1	0.80
AGB	kg/ha	6602	6506	−96	560	0.91
Grain yield	kg/ha	2627	2464	−163	257	0.97
SL 423						
Anthesis	DAP	60	63	3	5	0.52
Physiological maturity	DAP	86	87	1	2	80
LAI-Max	m^2/m^2	3.2	3.4	0.2	0.3	0.85
Leaf Number		12	13	0.5	1	0.75
AGB	kg/ha	6226	6590	−35.8	640	0.83
Grain yield	kg/ha	2736	2432	−305	698	0.64
Thialack 2						
Anthesis	DAP	61	60	−1	3	0.73
Physiological maturity	DAP	85	87	2	4	0.86
LAI-Max	m^2/m^2	3.15	3.27	0.1	0.3	0.82
Leaf Number		13	14	1	1	0.79
AGB	kg/ha	6096	6062	−34	208	0.98
Grain yield	kg/ha	2666	2706	40	389	0.78

AGB: Aboveground biomass.

micro-dosing approach during the years 2022 and 2023. The accuracy and reliability of the model were assessed by calculating the statistical indices between observed and simulated values shown in Eqs. (1)–(4). The model demonstrated satisfactory AGB and grain yield agreement between the simulated and observed data across the three clusters. The coefficient of agreement (d-index) ranges from 0.74 to 0.83 for AGB and from 0.64 to 0.98 for grain yield (Fig. 3). Deeply, in Daga Birame, the nRMSE of Souna 3 was 9.5 and 14.1% for AGB and grain yield respectively while it was 10.8 and 17.4% for SL 28 (Fig. 3A, B). In Meouane, nRMSE of Souna 3 was 11.8 and 15.3% for AGB and grain yield respectively while SL423 exhibited nRMSE equal to 14.8% for AGB and 16.7% for grain (Fig. 3C, D). In the last cluster, Thiel, nRMSE of Souna 3 was 18.1% for AGB and 12.5% for grain yield while it was 18.2 and 14.1% for Thialack 2 (Fig. 3E, F).

SEASONAL EFFECT OF PLANT POPULATION AND FERTILIZATION STRATEGIES ON PEARL MILLET YIELD

Millet cultivar/variety

The statistical analysis revealed that dual-purpose varieties outperformed the farmer's common variety, Souna 3, across all locations. The performance was significantly different ($P < 0.05$) in Daga Birame, where dual-purpose varieties exhibited a higher yield (Fig. 4). Despite this, the coefficient of variation (CV) indicated very high variability, for both varieties across the locations and a bit more pronounced for dual-purpose, particularly in Daga Birame and Thiel. However, in Meouane the CV for dual-purpose varieties was slightly lower than that of the farmer's variety.

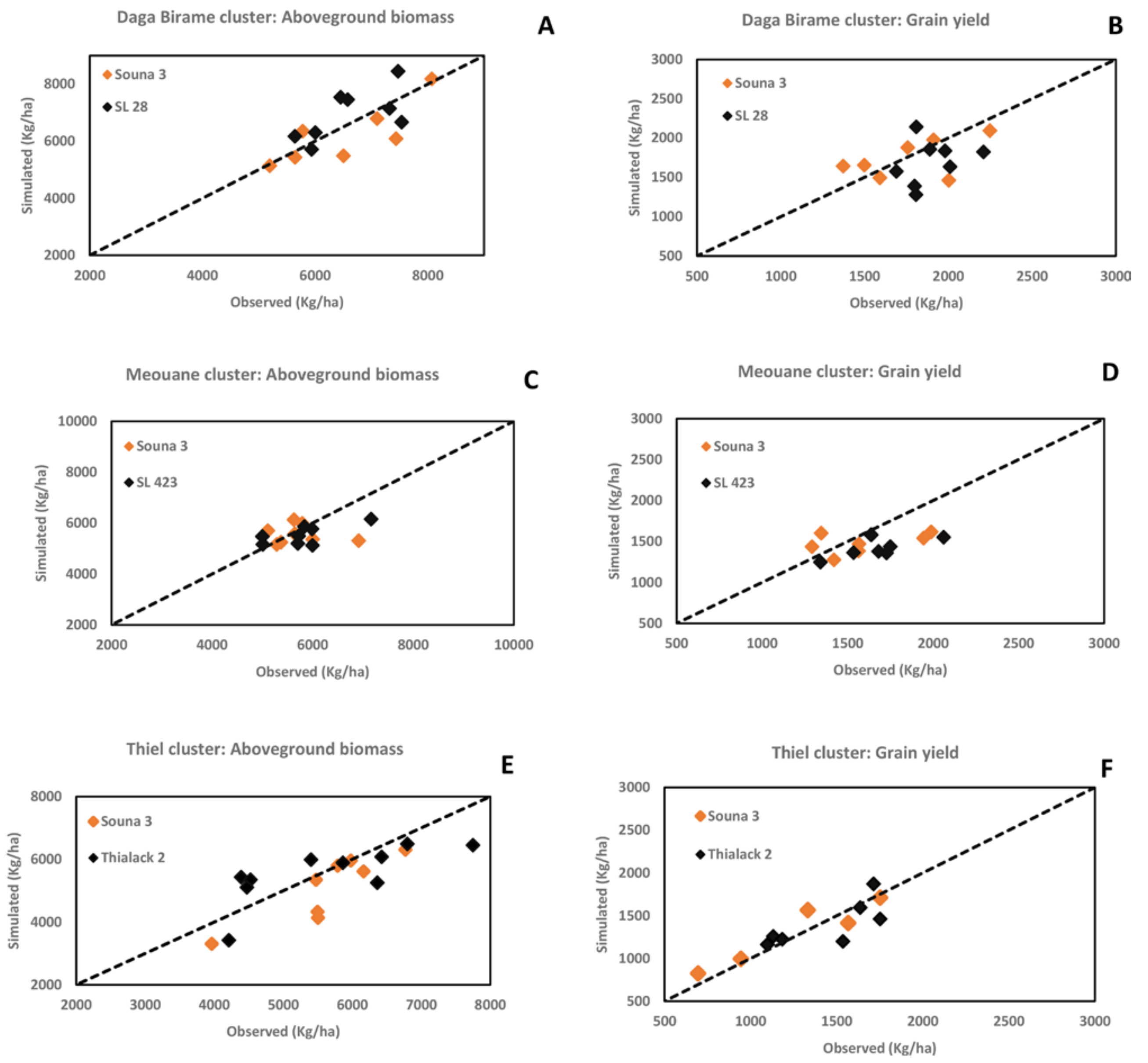

Fig. 3. Simulated vs observed for aboveground biomass (AGB), and grain yield for model evaluation across three clusters. Daga Birame cluster: (A) AGB Statistics: [*Souna 3:* MBE: −332, RMSE: 619, nRMSE: 9.5%, d-index: 0.87; *SL 28:* MBE: 312, RMSE: 717, nRMSE: 10.8%, d-index: 0.76]. (B) Grain yield Statistics: [*Souna 3:* MBE: −25, RMSE: 251, nRMSE: 14.1%, d-index: 0.83; *SL 28:* MBE: −207, RMSE: 332, nRMSE: 17.4%, d-index: 0.78]. Meouane cluster: (C) AGB Statistics: [*Souna 3:* MBE: −158, RMSE: 677, nRMSE: 11.8%, d-index: 0.80; *SL 423:* MBE: −273, RMSE: 546, nRMSE: 14.8%, d-index: 0.74]. (D) Grain yield Statistics: [*Souna 3:* MBE: −119, RMSE: 244, nRMSE: 15.3%, d-index: 0.68; *SL 423:* MBE: −233, RMSE: 280, nRMSE: 16.7%, d-index: 0.64]. Thiel cluster: (E) AGB Statistics: [*Souna 3:* MBE: −1086, RMSE: 1024, nRMSE: 18.1%, d-index: 0.83; *Thialack 2:* MBE: −125, RMSE: 1023, nRMSE: 18.2%, d-index: 0.83]. (F) Grain yield Statistics: [*Souna 3:* MBE: 57, RMSE: 158, nRMSE: 12.5%, d-index: 0.98; *Thialack 2:* MBE: −45, RMSE: 202, nRMSE: 14.1%, d-index: 0.98].

Plant population

High-plant population (25,000 hills/ha) showed good performance across the clusters over the 31 years of simulation, with significant differences noted in Meaoune and Thiel ($P < 0.05$). However, this treatment also exhibited a pronounced variability, as evidenced by the CV, which ranged from 39.1 to 47.9% (Fig. 5).

Micro-dosing fertilizer strategy

The effect of fertilizer application was significant ($P < 0.05$) across all clusters over the 31 years (Fig. 6). The CV for the first three levels of micro-dosing applications in Daga Birame and Thiel ranged from 9.4 to 26.1%, indicating moderate variability. In contrast, the CV was very high (37.2 to 41.7%) in Meouane, suggesting more year-to-year variability. Among the fertilizer levels, F3 (75 kg of NPK (15-15-15), 50 kg Urea, and 1.125 tons of cow manure) consistently demonstrated the lowest CV across all locations, highlighting its stability and effectiveness in reducing yield variability over time.

PROBABILITY OF EXCEEDANCE

The probability of exceedance was used to explain further the chances of simulating attainable yield thresholds for Souna 3 vis a vis dual-purpose varieties (SL 28, SL 423, and Thialack 2) across microdosing fertilizer applications in each cluster (Fig. 7). The analysis over 31 years revealed distinct performance outcomes for each variety across different micro-dosing fertilizer levels (F1, F2, F3, F4). Indeed, for more appreciation of the climate-smart practices such as ISFM strategy and dual-purpose varieties on a farm scale, information was investigated in the platform of the division of statistics of the agricultural ministry of Senegal (Available at: https://senegal.opendataforafrica.org, accessed 19 September 2024).

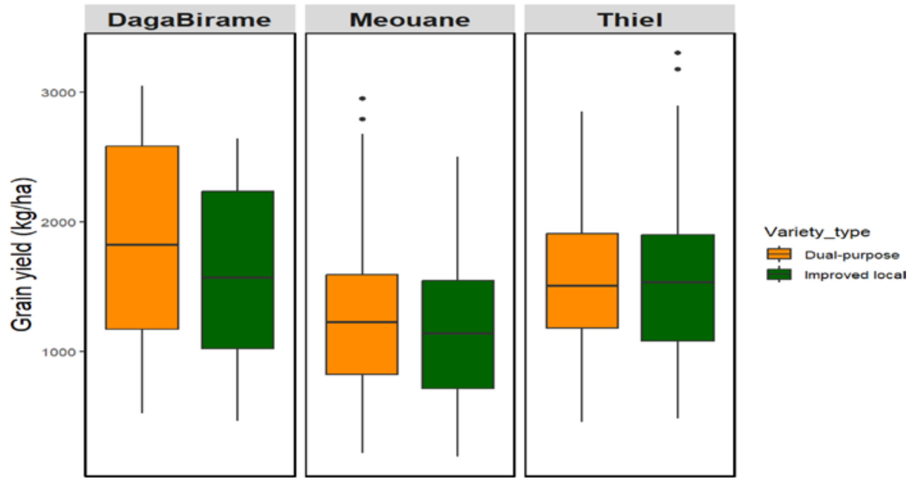

Fig. 4. Comparison of the performance of Dual-purpose varieties (SL 28, SL 423, and Thialack 2) vis-à-vis farmer-improved local (Souna 3) for simulated grain yield over 31 years in Daga Birame (SL 28 and Souna 3), Meoaune (SL 423 and Souna 3), and Thiel (Thialack 2 and Souna 3). In Daga Birame (CV of SL 28=38.8, Souna 3=36.2 and P<0.05); Meouane (CV of SL 423=44.2 and Souna 3=45.4) and Thiel (CVof Thialack 2=45.3 and Souna 3=44.4).

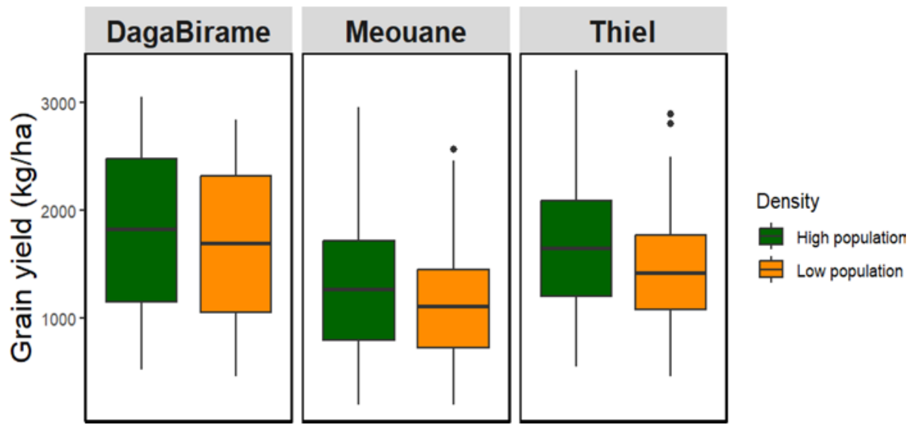

Fig. 5. Comparison of the model performance for two plant populations (high-population and low-population) on grain yield over 31 years. In Daga Birame (CV of HP=39.1 and LP=36.6), Meouane (CV of HP=47.9, LP=44.1, and P < 0.05), and Thiel (CV of HP = 39.8, LP = 38.4, and P < 0.05).

In Kaffrine region, the wettest location, the actual average grain yield from 2010 to 2022 was 1074 kg ha^{-1} while it was around 500 kg ha^{-1} and 700 kg ha^{-1} for Louga and Thies regions, respectively. Based on this, to improve food security, the desirable yield for the Daga Birame location (Kaffrine region) was defined as 1500 kg ha^{-1} while it was 1000 kg ha^{-1} for Thiel and Meoaune locations.

The results of our long-term simulation showed that in Daga Birame cluster, farmers have a 100% chance that yields will exceed 1500 kg/ha under microdosing fertilizer levels F1 and F2 (F1=150 kg/ha NPK and 100 kg/ha of urea; F2=150 kg/ha NPK, 100 kg/ha of urea, and 2.5 tons of cow manure) whetter for dual-purpose or farmers' improved variety. When farmers applied F3=75 kg/ha NPK, 50 kg/ha of urea, and 1.25 tons of cow manure, they had 20% under improved local while it was 40% for dual-purpose variety. Regarding the fertilizer level F4 = 75 kg/ha NPK, and 2.5 tons of cow manure, farmers have a 0% chance of getting yield up to 1500 kg/ha for both variety types (Fig. 7A, B). In Meouane, the probability of exceeding the 1000 kg/ha threshold under micro-dosing fertilizer applications F1 and F2 was 80% for both variety types. Farmers adopting micro-dosing fertilizer applications F3 would give them 60% chance to exceed 1000 kg/ha threshold whetter growing dual-purpose or improved local variety. For fertilizer F4, the probability of exceeding 1000 kg/ha threshold was 30 and 35% for improved local and dual-purpose variety respectively (Fig. 7C, D). In Thiel, growing dual-purpose variety (Thialack 2), yield can exceed 1000 kg/ha with a 98% chance while is 90% for improved local under micro-dosing fertilizer applications F1 and F2. Under F3 adoption, both variety types recorded a 90% chance of exceeding 1000 kg/ha. Also, the probability of exceeding 1000 kg/ha for dual-purpose was 68% with the application of F4 and 40% for improved local (Fig. 7E, F).

Discussion

The satisfactory agreement observed between simulated and observed phenological data for both days to anthesis and maturity across four contrasting environments of four selected cultivars underscores the robustness of the CERES-millet model within the DSSAT framework. The application of the CERES-millet model of DSSAT for simulating millet varieties under varying conditions underscores the value of modeling approaches in understanding and predicting crop performance (Mohamed *et al.*, 2023). Statistical indices, including lower RMSE and a good coefficient of agreement (d-index), ranging from 0.52 to 0.91 for anthesis and from 0.80 to 0.86 for maturity date, highlight the model's capability to accurately predict phenological stages under varying environmental conditions which is in line with Garba *et al.* (2024) who also found a good agreement for phenological parameters of millet across two agroecological zones in Niger. This further aligns with findings from previous studies such as those by Soler *et al.* (2008) and Ullah *et al.* (2019), emphasizing the model's adaptability across arid and

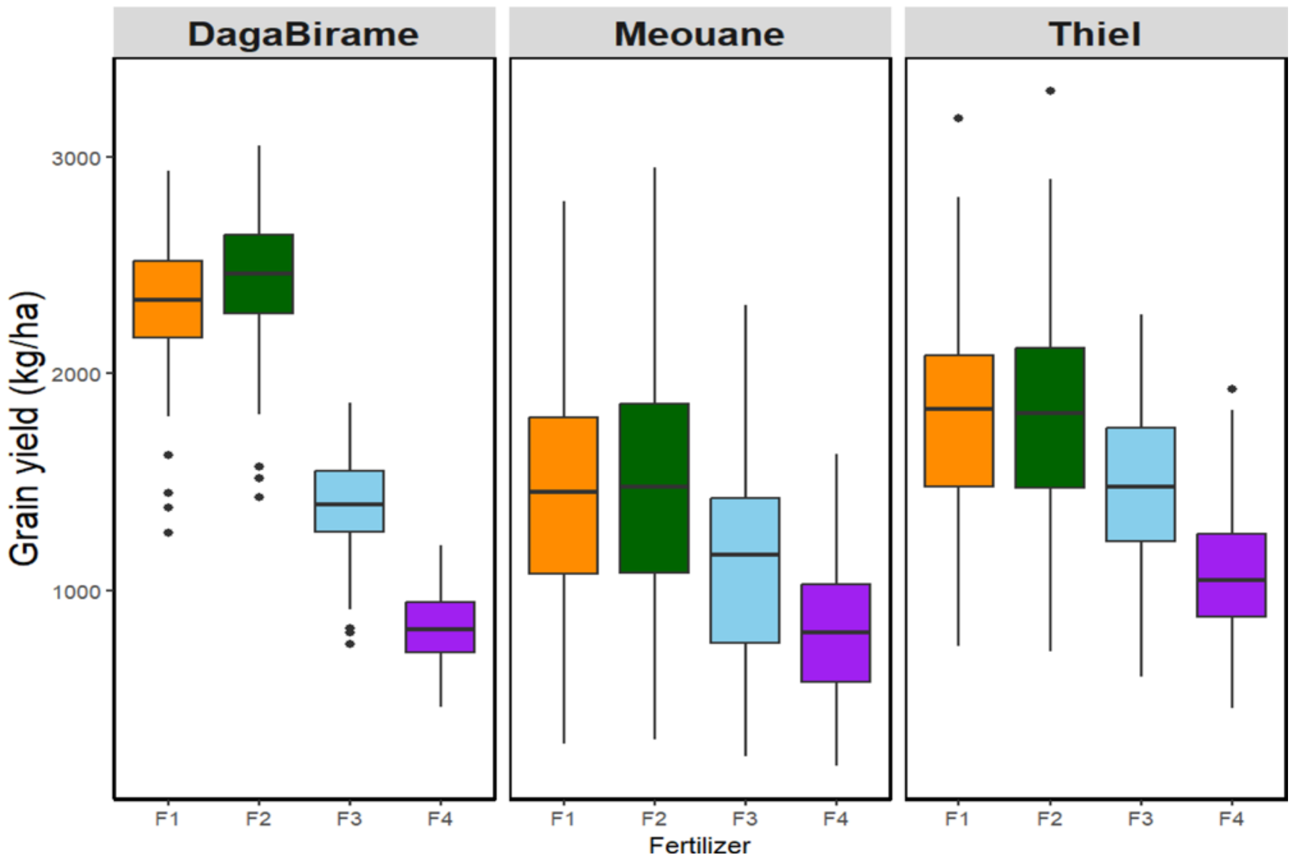

Fig 6. Simulated grain yield over 31 years using micro-dosing techniques for different fertilizer strategies. In Daga Birame (CV of F1=12, F2=11.8, F3=9.4, and F4=38.4), Meouane (CV of F1=41.7, F2=41.2, F3=37.2, and F4=38.1) and Thiel (CV of F1=26.1, F2=25.7, F3=23.4, and F4=43.2). (F1: 150 kg of NPK (15:15:15) + 100kg of urea (46%N), F2: 150 kg/ha (NPK)+ 100kg/ha (urea) + 2.5 ton/ha cow manure, F3: 75 kg/ha(NPK)+ 50 kg/ha (Urea) +1.25 ton/ha cow manure, F4: 75 kg/ha(NPK) + 2.5 ton/ha (cow manure).

semi-arid climates for crops such as millet. Furthermore, Akinseye *et al*. (2017), Tovihoudji *et al*. (2019), and Ullah *et al*. (2019) have proven that DSSAT has the potential to simulate phenology reasonably well under semi-arid climatic conditions respectively under sorghum, maize, and millet production.

Moreover, the CERES-millet model demonstrates its proficiency in simulating crop growth parameters, notably the LAI and leaf number, with statistical indices indicating a good agreement coefficient ranging from 0.62 to 0.85 and 0.75 to 0.8, respectively. Jones *et al*. (2003) extended these findings by demonstrating the model's applicability in simulating crop growth and development in semi-arid zones, applicable to both monoculture and intercrop systems. Therefore, the model overestimated LAI for the three dual-purpose varieties (SL 28, SL 423, and Thialack 2) except for the farmer common local variety (Souna 3). This is in line with Fechter *et al*. (1991) who found that the CERES-millet model overestimated LAI by 46%. Additionally, the model exhibited good agreement for AGB and grain yield predictions, with d-index values ranging from 0.83 to 0.98 for AGB and 0.64 to 0.97 for grain yield, alongside lower RMSE values (Table 4). This suggests the model's effectiveness across different planting densities and environmental contrasts as also mentioned by Garba *et al*. (2024). Ullah *et al*. (2019) highlighted the model's success in simulating plant density and nitrogen application effects in arid and semi-arid conditions in Pakistan, while Soler *et al*. (2008) noted the CSM–CERES-Millet model's accuracy in simulating growth, development, and yield for millet in two contrasting environments. White *et al*. (2015) also reported favorable outcomes for maximum LAI, AGB, and grain yield simulations under the CERES-sorghum model. Furthermore, the model effectively evaluated AGB and grain yield across different micro-dosing organo-mineral fertilizer levels at the farm scale, with lower RMSE values ranging from 281 to 789 kg ha^{-1} and 144 to 332 kg ha^{-1}. These findings underscore the model's utility in accurately simulating crop growth dynamics across various agronomic conditions. Specifically, the DSSAT's ability to accurately simulate AGB and grain yield at the farm scale, particularly with micro-dosing strategies, presents a valuable tool for decision making of the four varieties in semi-arid regions of Senegal, and potentially beyond. The analysis of long-term weather information highlights significant year-to-year variability in rainfall across the clusters, which can have implications for agricultural productivity. The observed trends in increased rainfall and the negative correlation between the onset and length of the growing season offer valuable insights into the most important factors that control a longer growing season (Akinseye *et al*., 2017).

In that case, adaptive strategies to cope with climatic variability can help optimize crop yields and ensure sustainable farming practices. Thereby, seasonal analysis was done after a successful evaluation of the model to figure out the optimum fertilizer rate and plant density for each location vis-a-vis of farmers' practices offering practical guidance for sustainable and efficient agricultural practices. In the context of evaluating the performance of newly released millet varieties alongside smart agricultural practices such as the use of dual-purpose variety, increased planting density, and micro-dosing, against traditionally farmed practices, our study reveals significant insights. Over a 31-year simulation period, the results indicate that high-density planting consistently outperformed lower density across the three clusters, with statistically significant differences observed in Meaouane and Thiel ($P < 0.05$). The great performance associated with higher plant density in Meouane

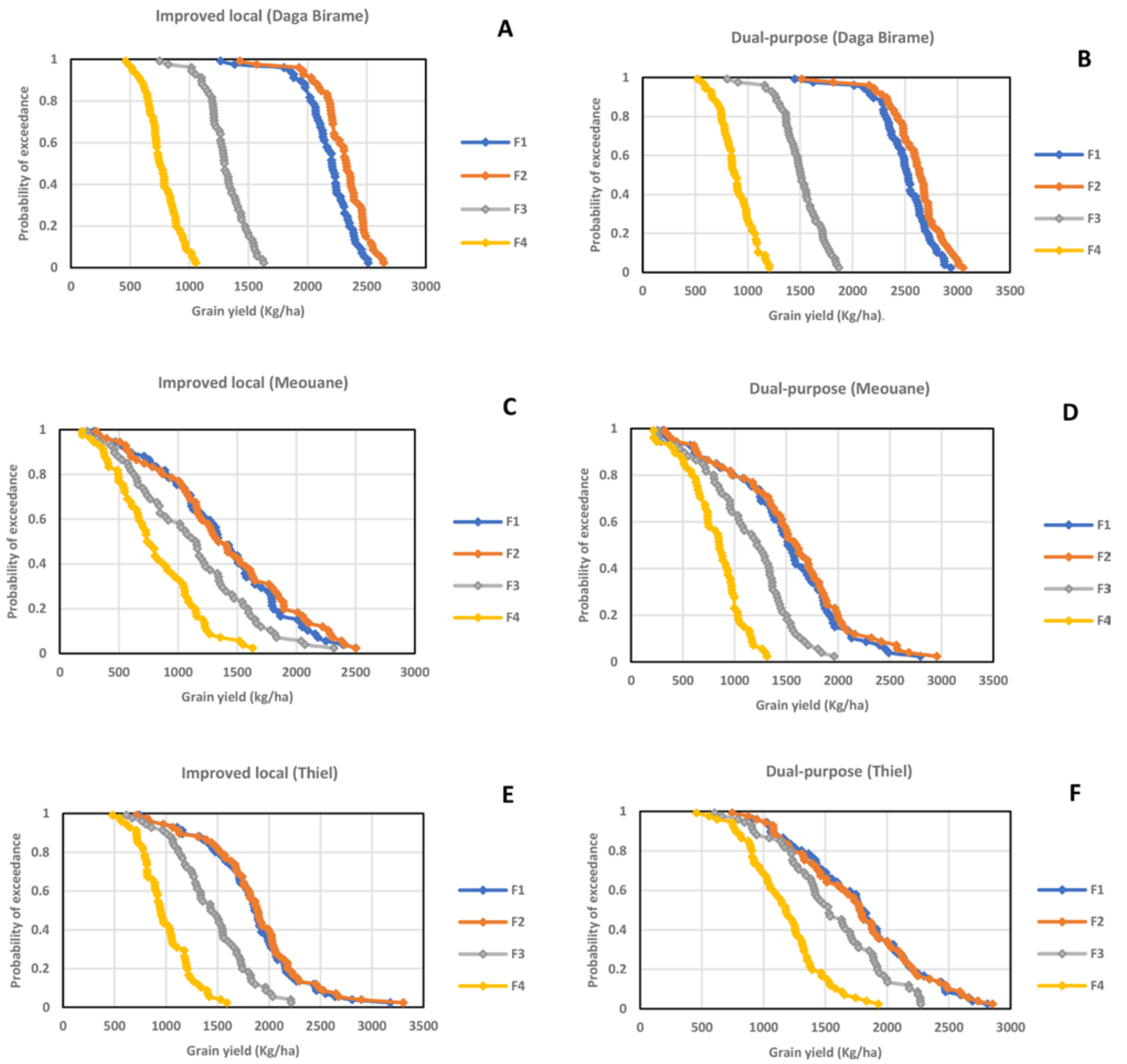

Fig. 7. Probability of exceedance for simulated grain yield of improved local variety (Souna 3) vis a vis of dual-purpose varieties (Thialack 2, SL 28, and SL 423) for fertilizer strategies application over 31 years across the three rainfall gradients. (F1:150kg of NPK (15:15:15) + 100kg of Urea(46%N), F2: 150kg/ha (NPK)+ 100kg/ha (Urea) + 2.5ton/ha cow manure, F3: 75kg/ha(NPK)+ 50kg/ha (Urea) +1.25ton/ha cow manure, F4: 75kg/ha(NPK) + 2.5 ton/ha (Cow manure)).

and Thiel further illustrates the importance of optimizing planting density as a smart agricultural practice to enhance yields in drier regions. This is in line with Faye *et al*. (2023) and Pilloni *et al*. (2022) who found that increasing the plant density to 25,000 hill/ha enhance significantly millet fodder and grain yield in Senegal. The performance of high density can likely be attributed to the good vegetation cover associated with higher plant populations, which could reduce evapotranspiration and keep more soil moisture. Nonetheless, this approach seems to entail a more associated risk compared to low density, as indicated by the greater coefficient of variation compared to low densities over the 31-year simulation period across the three locations. Also, the CV was observed to be considerably high for both improved local and dual-purpose millet varieties, with more pronounced dual-purpose varieties for two locations. This implies that farmer common variety is a bit more stable than dual-purpose varieties which is also observed by Faye *et al*. (2023). This is corroborated results of Sultan *et al*. (2013) who found that the traditional cultivars of millet and sorghum used by local farmers seem to be more resilient to climate-changing conditions compared to improved high-yield potential cultivars. However, the slightly lower value of CV of dual-purpose compared to improved local variety in the driest cluster highlighted that dual-purpose can also be well suitable adapted to drought conditions and performs better. Indeed, the dual-purpose variety exhibited better performance in all three locations compared to improved local with a significant effect in Daga Birame (Fig. 4). Akinseye *et al*. (2024) also using the APSIM model, noted the good performance of dual-purpose millet variety compared to improved local when farmers sow on optimum windows in Senegal. This suggests that dual-purpose varieties may offer advantages in terms of yield potential under certain fertilizer management strategies. This justifies that dual-purpose millet varieties have been chosen to generate high-quality fodder without compromising grain production (Faye *et al*., 2023; Tounkara *et al*., 2020). Besides, the overall good performance of both types of variety (Souna 3 and dual-purpose) recorded across the locations compared to the range of farmers' actual yield, underscores the critical role of effective management practices. The use of ISFM techniques and improved plant population, even when using traditional farmer varieties, can significantly boost yields. This highlights the potential for improving agricultural productivity through better management practices, even in regions with challenging growing conditions. Tounkara *et al*. (2023) highlighted how the use of micro-dosing technology increased grain yield in Senegal by 62% when compared to farmers' practices and by 148% when compared to the control. Badiane *et al*. (2001) underlined that in Senegal's semi-arid agroecological zone, millet output significantly increased when farmers applied both mineral and organic fertilizers. They further highlighted that the efficiency of the fertilizer applied was better with the micro-dosing technology than with the recommended rate. Indeed, Hayashi *et al*. (2008) noted that the application of micro-dosing alone increases millet yield by 56% above the control. But combining with crop residue or manure increased millet grain yield to 140% over the control.

This finding aligns with the broader literature on the importance of tailoring fertilizer use to specific soil properties and environmental conditions in sub-Saharan Africa and the optimization of fertilizer use within the context of ISFM (Maman *et al*., 2018). Moreover, the study highlights the substantial impact of fertilizer application across all clusters over 31 years. The CV was moderate, ranging from 9.4 to 26.1%, for micro-dosing application F1, F2, and F3 in Daga Birame and Thiel clusters, indicating a slight yield variability. However, in Meaoune, the CV was exceptionally high, ranging from 37.2 to 41.7%, suggesting a higher degree of unpredictability in yield outcomes. This emphasized that the yield variability under fertilizer application increases toward the driest location which can be linked to the high variability (24%) of rainfall in this area from 1990 to 2020. Despite these variations, micro-dosing fertilizer application strategy F3 (75 kg/ha NPK, 50 kg/ha urea, and 1.25 tons of cow manure) emerged as the most stable, showing lower year-to-year variability compared to other fertilizer strategies across the clusters (Fig. 6). This stability suggests that F3 could be a more reliable and affordable option for farmers, making it a suitable candidate for adoption by smallholder farmers. The results also showed the combination of organic manure and mineral recommended rate in Senegal has a beneficial impact only in the wettest location Daga Birame with a good performance of F2. The process of organic manure mineralization and its uptake by crops is significantly influenced by abiotic factors such as soil conditions, humidity, and rainfall patterns (Liu *et al*., 2024). The results from the study indicate that the combination of organic manure and mineral fertilizer at the recommended rate in Senegal is most beneficial in the wettest location, Daga Birame. This suggests that organic amendments are more effective in areas with relatively higher rainfall and better soil conditions. Good rainfall patterns enhance the mineralization process by providing consistent moisture, which is crucial for microbial activity that breaks down organic matter into plant-available nutrients (Adekiya *et al*., 2020). Additionally, adequate rainfall ensures that these nutrients are readily accessible to crops.

CONCLUSIONS

Our study underscores the significance of innovative agricultural practices in enhancing the resilience and productivity of smallholder farmers in dryland farming systems. It focuses on dual-purpose millet varieties and micro-dosing fertilizer strategies, demonstrating their potential to improve crop yields in challenging environments. We utilized a model that accurately simulated phenology, morphology, grain yield, and AGB for various millet cultivars across different environments. Seasonal simulations revealed that dual-purpose cultivars (SL 28, SL 423, and Thialack2) consistently outperformed the traditional Souna 3 variety, despite showing some year-to-year yield variability. A probability of exceedance analysis highlighted the advantages of combining dual-purpose cultivars with micro-dosing fertilizer applications. This combination achieved higher yield thresholds compared to Souna 3 across various locations. The study identified a particularly stable and affordable micro-dosing fertilizer strategy (level 3), consisting of 3g/hill of NPK, 2g/hill of urea, and 50 g/hill of cow manure. This approach effectively reduced yield variability under changing conditions in Senegal's semi-arid zones and beyond. Two other micro-dosing fertilizer levels, F1 (6g/hill of NPK + 4g/hill of Urea) and F2 (6g/hill of NPK + 4g/hill of urea + 100g/hill of cow manure), also showed good yield performance across locations, albeit with higher year-to-year variability than level 3.

Our findings offer valuable insights for smallholder farmers, suggesting that adopting dual-purpose cultivars and optimized fertilizer strategies can significantly enhance millet productivity and sustainability in dryland environments infested with multiple challenges. The study recommends using these micro-dosing fertilizer strategies alongside the tested dual-purpose millet varieties in each cluster to achieve higher productivity. The research serves as a foundation for promoting ISFM in millet production, particularly in regions facing challenging and changing climatic conditions. However, future studies should assess the profitability of each micro-dosing fertilizer strategy and plant density, considering various economic factors such as input costs, market prices, and potential yield gains under different environmental conditions.

CONFLICT OF INTEREST

The authors report no competing interests to declare.

ETHICS STATEMENT

The authors confirm that the research meets any required ethical guidelines, including adherence to the legal requirements of the study country.

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AUTHOR CONTRIBUTIONS

Inoussa Zagre: Conceptualization, Methodology, Investigation, Data acquisition and curation, analysis, Writing – original draft and editing. Nadine O. Worou: Conceptualization, Methodology, Writing – review & editing, Project administration. Folorunso M. Akinseye: Conceptualization, Methodology, Investigation, Data acquisition and curation, Writing – review & editing. Jacob E. Joseph: Methodology, Writing – review & editing. Aliou Faye: Methodology, Writing – review & editing. Mama Kone: Methodology, Writing – review & editing. Anthony M. Whitbread: Writing – review & editing, and funding acquisition.

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DATA AVAILABILITY

Data will be made available on request.

References

Adam, M., MacCarthy, D.S., Traoré, P.C.S., Nenkam, A., Freduah, B.S., Ly, M. and Adiku, S.G.K. (2020) Which is more important to sorghum production systems in the Sudano-Sahelian zone of West Africa: Climate change or improved management practices? *Agricultural Systems* 185, 102920. DOI: 10.1016/j.agsy.2020.102920.

Adekiya, A.O., Ejue, W.S., Olayanju, A., Dunsin, O., Aboyeji, C.M. *et al.* (2020) Different organic manure sources and NPK fertilizer on soil chemical properties, growth, yield and quality of okra. *Scientific Reports* 10(1), 1–9. DOI: 10.1038/s41598-020-73291-x.

Adiku, S.G.K., Maccarthy, D.S., Hathie, I., Diancoumba, M., Freduah, B.S. *et al.* (2015) *Climate Change Impacts on West African Agriculture: An Integrated Regional Assessment (CIWARA)*. Imperial College Press, London. DOI: 10.1142/p970#t=toc.

Ajeigbe, H.A. and Dashiell, K. (2010) *Participatory Research Extension Approach: N 2 Africa Extension Method Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa (N 2 Africa)*. Available at: www.iita.org (accessed 11 July 2024).

Akinseye, F.M., Agele, S.O., Traore, P.C.S., Adam, M. and Whitbread, A.M. (2016) Evaluation of the onset and length of growing season to define planting date—'a case study for Mali (West Africa).' *Theoretical and Applied Climatology* 124(3–4), 973–983. DOI: 10.1007/s00704-015-1460-8.

Akinseye, F.M., Adam, M., Agele, S.O., Hoffmann, M.P., Traore, P.C.S. and Whitbread, A.M. (2017) Assessing crop model improvements through comparison of sorghum (sorghum bicolor L. moench) simulation models: A case study of West African varieties. *Field Crops Research* 201, 19–31. DOI: 10.1016/j.fcr.2016.10.015.

Akinseye, F.M., Birhanu, B.Z., Ajeigbe, H.A., Diancoumba, M., Sanogo, K. and Tabo, R. (2023a) Impacts of fertilization management strategies on improved sorghums varieties in smallholder farming systems in Mali: Productivity and profitability differences. *Heliyon* 9(3), e14497. DOI: 10.1016/j.heliyon.2023.e14497.

Akinseye, F.M., Ajeigbe, H.A., Kamara, A.Y., Omotayo, A.O., Tofa, A.I. and Whitbread, A.M. (2023b) Establishing optimal planting windows for contrasting sorghum cultivars across diverse agro-ecologies of north-eastern nigeria: A modelling approach. *Agronomy* 13(3), 727. DOI: 10.3390/agronomy13030727.

Akinseye, F.M., Zagre, I., Faye, A., Joseph, J.E., Worou, O.N. and Whitbread, A.M. (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, 1428630. DOI: 10.3389/fagro.2024.1428630.

Akponipke (2008) *Millet Response to Water and Soil Fertility Management in the Sahelian Niger: Experiments and Modeling*. Doctorat thesis, Université catholique de Louvain, 200 p.

Almazroui, M., Saeed, F., Saeed, S., Nazrul Islam, M., Ismail, M., Klutse, N.A.B. and Siddiqui, M.H. (2020) Projected change in temperature and precipitation over Africa from CMIP6. *Earth Systems and Environment* 4(3), 455–475. DOI: 10.1007/s41748-020-00161-x.

Araya, A., Hoogenboom, G., Luedeling, E., Hadgu, K.M., Kisekka, I. and Martorano, L.G. (2015) Assessment of maize growth and yield using crop models under present and future climate in southwestern Ethiopia. *Agricultural and Forest Meteorology* 214–215, 252–265. DOI: 10.1016/j.agrformet.2015.08.259.

Araya, A., Jha, P.K., Zambreski, Z., Faye, A., Ciampitti, I.A. *et al.* (2022) Evaluating crop management options for sorghum, pearl millet and peanut to minimize risk under the projected midcentury climate scenario for different locations in Senegal. *Climate Risk Management* 36. DOI: 10.1016/j.crm.2022.100436.

Badiane, A., Faye, A., Yamoah, C.F. and Dick, R.P. (2001) Use of compost and mineral fertilizers for millet production by farmers in the semiarid region of Senegal. *Biological Agriculture and Horticulture* 19(3), 219–230. DOI: 10.1080/01448765.2001.9754926.

Beah, A., Kamara, A.Y., Jibrin, J.M., Akinseye, F.M., Tofa, A.I. and Adam, A.M. (2021) Simulating the response of drought-tolerant maize varieties to nitrogen application in contrasting environments in the nigeria savannas using the APSIM model. *Agronomy* 11(1), 76. DOI: 10.3390/agronomy11010076.

Bélanger, G. (2000) *Impacts des Changements Climatiques sur l'agriculture au québec*. Agriculture and Agri-Food Canada (AAC), Sainte-Foy, Quebec.

Bowen, W. T., Thornton, P. K. and Hoogenboom, G. (1998) The simulation of cropping sequences using DSSAT. In: Tsuji, G.Y., Hoogenboom, G. and Thornton, P.K. (eds) *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, pp. 313–327.

CILSS (2017) *UEMOA Communaute Economiqu des Etats d'Afrique de l'Ouest é Comit Permanent Inter-Etats de Lutte contre la Sécheresse pour le Sahel é Union Economique et Monétaire Ouest Africaine 2016 Catalogue Régional des Espèces et Variétés Végétales CEDEAO-UEMOA-CILSS*.

Diatta, S. and Thomason, W.E. (2016) Improving pearl millet (*Pennisetum glaucum* (L.) R.Br.) productivity in saltaffected soils in Senegal: A greenhouse and field investigation. *Agronomy Journal* 108(6), 2345–2353.

Dodds, P.E. (2010) *Development of a Crop Model to Examine Crop Management and Climate Change in Senegal*. Ph.D thesis, University of Leeds, 276 p. DOI: 10.2134/agronj2016.03.0162.

Dov, P., Ibrahim, A. and Augustine, A. (2012) Evaluation of five pearl millet varieties for yield and forage quality under two planting densities in the Sahel. *African Journal of Agricultural Reseearch* 7(32), 4526–4535. DOI: 10.5897/ajar11.1569.

Falconnier, G.N., Descheemaeker, K., Traore, B., Bayoko, A. and Giller, K.E. (2018) Agricultural intensification and policy interventions: Exploring plausible futures for smallholder farmers in Southern Mali. *Land Use Policy* 70, 623–634. DOI: 10.1016/j.landusepol.2017.10.044.

FAO (1993) FESLM: An international framework for evaluating sustainable land management Table of contents World Soil Resources Report Food and Agriculture Organization of the United Nations 1993 A Discussion Paper. 73, 85.

Faye, N.F., Diagne, A., Sawadogo, K. and Dia, D. (2018) Impact of adoption of improved pearl millet varieties on productivity in Central Senegal. *Journal of Agriculture and Environmental Sciences* 7(2), 90–100. DOI: 10.15640/jaes.v7n2a10.

Faye, A., Akplo, T.M., Stewart, Z.P., Min, D., Obour, A.K., Assefa, Y. and Prasad, P.V.V. (2023) Increasing millet planting density with appropriate fertilizer to enhance productivity and system resilience in Senegal. *Sustainability (Switzerland)* 15(5), 4093. DOI: 10.3390/su15054093.

Fechter, J., Allison, B.E., Sivakumar, M.V.K., Van Der Ploeg, R.R. and Bley, J. (1991) *An Evaluation of the SWATRER and CERES-Millet Models for Southwest Niger (Issue 199)*. IAHS Publ.

Garba, M., Kamara, A.Y., Mohamed, A.M.L., Tofa, A.I., Mahamane, S.A. *et al.* (2024) Assessing the effects of plant density and nitrogen on millet yield in Southern Niger using the CERES-millet model. *CABI Agriculture and Bioscience* 5(1), 50. DOI: 10.1186/s43170-024-00254-x.

Gijsman, A.J., Jagtap, S.S. and Jones, J.W. (2002) Wading through a swamp of complete confusion: How to choose a method for estimating soil water retention parameters for crop models. *European Journal of Agronomy* 18(1–2), 77–106. DOI: 10.1016/s1161-0301(02)00098-9.

Gueye, M., Kanfany, G., Fofana, A., Gueye, M., Noba, K. and Grove, J. (2015) Effect of planting date on growth and grain yield of fonio millet (*Digitaria exilis* Stapf) in the Southeast of Senegal. *International Journal of Biological and Chemical Sciences* 9(2), 581. DOI: 10.4314/ijbcs.v9i2.1.

Han, E., Ines, A.V.M. and Koo, J. (2019) Development of a 10-km resolution global soil profile dataset for crop modeling applications. *Environmental Modelling and Software* 119, 70–83. DOI: 10.1016/j.envsoft.2019.05.012.

Hayashi, K., Abdoulaye, T., Gerard, B. and Bationo, A. (2008) Evaluation of application timing in fertilizer micro-dosing technology on millet production in Niger. *West Africa. Nutrient Cycling in Agroecosystems* 80(3), 257–265. DOI: 10.1007/s10705-007-9141-3.

Hoogenboom, G., Porter, C.H., Boote, K.J., Shelia, V., Wilkens, P.W. *et al.* (2019) *The DSSAT Crop Modeling Ecosystem*, pp. 173–216. DOI: 10.19103/as.2019.0061.10.

IFDC (2016) *Final Report: External Strategic Review of the International Fertilizer Development Center (IFDC)*. USAID, Washington, DC, 115 p.

ISRA (2014) *Variétés de Mil*. ISRA, Senegal, pp. 60–67.

Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J. *et al.* (2021) Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food* 2(11), 873–885. DOI: 10.1038/s43016-021-00400-y.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D. *et al.* (2003) The DSSAT cropping system model. *European Journal of Agronomy* 18(3–4), 235–265. DOI: 10.1016/S1161-0301(02)00107-7.

Joseph, J.E., Akinseye, F.M., Worou, O.N., Faye, A., Konte, O., Whitbread, A.M. and Rötter, R.P. (2023) Assessment of the relations between crop yield variability and the onset and intensity of the West African Monsoon. *Agricultural and Forest Meteorology* 333, 109431. DOI: 10.1016/j.agrformet.2023.109431.

Kamara, A.Y., Garba, M., Tofa, A.I., Mohamed, A.M.L., Souley, A.M., Abdoulaye, T. and Kapran, B.I. (2023) Assessment of the impact of crop management strategies on the yield of early-maturing maize varieties in the drylands of Niger Republic: Application of the DSSAT-CERESMaize model. *Heliyon* 9(7), 23. DOI: 10.1016/j.heliyon.2023.e17829.

Koo, J., Cox, C.M., Bacou, M., Azzarri, C., Guo, Z. *et al.* (2016) CELL5M: A geospatial database of agricultural indicators for Africa South of the Sahara. *F1000Research* 5. DOI: 10.12688/f1000research.9682.1.

Lalou, R., Sultan, B., Muller, B. and Ndonky, A. (2019) Does climate opportunity facilitate smallholder farmers' adaptive capacity in the Sahel? *Palgrave Communications* 5(1), 1–11. DOI: 10.1057/s41599-019-0288-8.

Liu, Y., Lan, X., Hou, H., Ji, J., Liu, X. and Lv, Z. (2024) Multifaceted ability of organic fertilizers to improve crop productivity and abiotic stress tolerance: Review and perspectives. *Agronomy* 14(6), 1141. DOI: 10.3390/agronomy14061141.

Loague, K. and Green, R.E. (1991) Statistical and graphical methods for evaluating solute transport models: Overview and application. *Journal of Contaminant Hydrology* 7, 51–73.

Lobell, D.B. and Burke, M.B. (2010) On the use of statistical models to predict crop yield responses to climate change. *Agricultural and Forest Meteorology* 150(11), 1443–1452. DOI: 10.1016/j.agrformet.2010.07.008.

MacCarthy, D.S., Vlek, P.L.G., Bationo, A., Tabo, R. and Fosu, M. (2010) Modeling nutrient and water productivity of sorghum in smallholder farming systems in a semi-arid region of Ghana. *Field Crops Research* 118(3), 251–258. DOI: 10.1016/j.fcr.2010.06.005.

Maman, G., Idriss, S. and Wortmann, C. (2018) Crop yield response to fertilizer relative to soil properties in Sub-Saharan Africa. *Soil Science Society of America Journal* 82(4), 862–870. DOI: 10.2136/sssaj2018.02.0066.

Mohamed, A.M.L., Jibrin, J.M., Auwalu, B.M., Garba, M. and Lawan, B.A. (2023) Application of Ceres-Millet model of DSSAT for simulating millet varieties under different sowing windows in Niger. *Journal of Crop Improvement* 37(1), 41–59. DOI: 10.1080/15427528.2022.2048764.

Nissanka, S.P., Karunaratne, A.S., Perera, R., Weerakoon, W.M.W., Thorburn, P.J. and Wallach, D. (2015) Calibration of the phenology sub-model of APSIM-Oryza: Going beyond goodness of fit. *Environmental Modelling and Software* 70, 128–137. DOI: 10.1016/j.envsoft.2015.04.007.

Perez, C., Jones, E.M., Kristjanson, P., Cramer, L., Thornton, P.K., Forch, W. and Barahona, C. (2015) How resilient are farming households and communities to a changing climate in Africa? A gender-based perspective. *Global Environmental Change* 34, 95–107. DOI: 10.1016/j.gloenvcha.2015.06.003.

Pickering, N.B., Hansen, J.W., Jones, J.W., Wells, C.M., Chan, V.K. *et al*. (1994) WeatherMan: A utility for managing and generating daily weather data. *Agronomy Journal* 86(2), 332–337.

Pilloni, R., Faye, A., Kakkera, A., Kholova, J., Badji, R., Faye, C. and Vadez, V. (2022) Higher sowing density of pearl millet increases productivity and water use efficiency in high evaporative demand seasons. *Frontiers in Plant Science* 13, 1035181. DOI: 10.3389/fpls.2022.1035181.

Reddy, C.R., Khan, A.A., Prasad, K.V.S.V, Ravi, D., Reddy, B.S.V. *et al.* (2010) Stover quality traits for improvement of dual-purpose sorghum. *Animal Nutrition and Feed Technology* 10S, 113–119. DOI: 10.2134/agronj1994.00021962008600020023x.

Ritchie, J.T. (1981) Soil water availability. *Plant and Soil* 58(1–3), 327–338. DOI: 10.1007/BF02180061.

Ritchie, J.T., Singh, U., Godwin, D.C., Bowen, W.T. and Peru, L. (1998) Cereal growth, development and yield. In: Tsuji, G.Y., Hoogenboom, G. and Thornton, P.K. (eds) *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, pp. 79–114.

Salack, S., Muller, B. and Gaye, A.T. (2011) Rain-based factors of high agricultural impacts over Senegal. Part I: Integration of local to sub-regional trends and variability. *Theoretical and Applied Climatology* 106(1–2), 1–22. DOI: 10.1007/s00704-011-0414-z.

Sivakumar. (1988) Predicting rainy season potential form the onset of the rins in southern sahelian and sudanian climatic zones of West Africa. *Agricultural and Forest Meteology* 42, 295–305.

Soler, C.M.T., Maman, N., Zhang, X., Mason, S.C. and Hoogenboom, G. (2008) Determining optimum planting dates for pearl millet for two contrasting environments using a modelling approach. *Journal of Agricultural Science* 146(4), 445–459. DOI: 10.1017/S0021859607007617.

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. *Environmental Research Letters* 8(1), 014040. DOI: 10.1088/1748-9326/8/1/014040.

Sultan, B., Defrance, D. and Iizumi, T. (2019) Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Scientific Reports* 9(1), 12834. DOI: 10.1038/s41598-019-49167-0.

Sultan, B., Ahmed, A.I., Faye, B. and Tramblay, Y. (2023) Less negative impacts of climate change on crop yields in West Africa in the new CMIP6 climate simulations ensemble. *Plos Climate* 2(12), e0000263. DOI: 10.1371/journal.pclm.0000263.

Tabo, R., Bationo, A., Gerard, B., Ndjeunga, J., Marchal, D. *et al*. (2007) Improving cereal productivity and farmers' income using a strategic application of fertilizers in West Africa. In: Bationo, A., Waswa, B., Kihara, B. and Vanlauwe, J. (eds) *Tropical Soil Biology and Fertility: A Handbook of Methods*. Springer, Dordrecht, pp. 201–208.

Tounkara, A., Clermont-Dauphin, C., Affholder, F., Ndiaye, S., Masse, D. and Cournac, L. (2020) Inorganic fertilizer use efficiency of millet crop increased with organic fertilizer application in rainfed agriculture on smallholdings in central Senegal. *Agriculture, Ecosystems & Environment* 294, 106878. DOI: 10.1016/j.agee.2020.106878.

Tounkara, A., Camara, B., Ndiaye, A., Gomis, E., Faye, M., Fall, T. and Ngom, D. (2023) Effects of microdose fertilization on sanio millet (Pennisetum glaucum (L.) R. Br) in low casamance (Southern Senegal). *International Journal of Agriculture, Environment and Bioresearch* 08(02), 139–149. DOI: 10.35410/IJAEB.2023.5823.

Toure, H.A., Serme, I., Traore, K. and Kyei-Baffour, N. (2018) Assessment of the changes in the yields of millet crop under different scenarios of climate change using DSSAT model. *International Journal of Biological and Chemical Sciences* 12(1), 363. DOI: 10.4314/ijbcs.v12i1.29.

Tovihoudji, P.G., Akponikpè, P.B.I., Agbossou, E.K. and Bielders, C.L. (2019) Using the DSSAT model to support decision making regarding fertilizer microdosing for maize production in the sub-humid region of Benin. *Frontiers in Environmental Science* 7(Feb), 13. DOI: 10.3389/fenvs.2019.00013.

Tsuji, G.Y., Uehara, G., Balas, S. and International Benchmark Sites Network for Agrotechnology Transfer., International Consortium for Agricultural Systems Application., & University of Hawaii (Honolulu) (1994) *DSSAT : Version 3*. International Benchmark Sites Network for Agrotechnology Transfer.

Ullah, A., Ahmad, I., Ahmad, A., Khaliq, T., Saeed, U. *et al.* (2019) Assessing climate change impacts on pearl millet under arid and semi-arid environments using CSM-CERES-Millet model. *Environmental Science and Pollution Research* 26(7), 6745–6757. DOI: 10.1007/s11356-018-3925-7.

Uppal, R.K., Wani, S.P., Garg, K.K. and Alagarswamy, G. (2015) Balanced nutrition increases yield of pearl millet under drought. *Field Crops Research* 177, 86–97. DOI: 10.1016/j.fcr.2015.03.006.

Weitkamp, T., Jan Veldwisch, G., Karimi, P. and de Fraiture, C. (2023) Mapping irrigated agriculture in fragmented landscapes of sub-Saharan Africa: An examination of algorithm and composite length effectiveness. *International Journal of Applied Earth Observation and Geoinformation*, 122. DOI: 10.1016/j.jag.2023.103418.

White, J.W., Alagarswamy, G., Ottman, M.J., Porter, C.H., Singh, U. and Hoogenboom, G. (2015) An overview of CERES–sorghum as implemented in the cropping system model version 4.5. *Agronomy Journal* 107(6), 1987–2002. DOI: 10.2134/agronj15.0102.

Willmot Cort, J. (1982) Some comments on the evaluation of model performance. *American Meteorological Society* 63(11), 1309–1317.

Zagre, I., Akinseye, F.M., Worou, O.N., Kone, M. and Faye, A. (2024) Climate change adaptation strategies among smallholder farmers in Senegal's semi-arid zone: Role of socio-economic factors and institutional supports. *Frontiers in Climate* 6, 1332196. DOI: 10.3389/fclim.2024.1332196.