



EVALUATING THE PERFORMANCE OF THE CERES-MAIZE MODEL FOR DECISION-SUPPORT IN NIGERIAN MAIZE PRODUCTION SYSTEMS

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ABSTRACT

The study focused on evaluating the performance of the CERES-Maize model within the DSSAT framework for simulating the growth and yield of three maize varieties (2016 TZdEE-Y, 2014 TZE-Y, and SAMMAZ-40) in the savanna region of Nigeria. Field experiments were conducted during the 2023 growing season across three locations in Kano state, representing both the Sudan and Northern Guinea Savannas. The experimental data, which included six different sowing dates, were used to validate the model. The results demonstrated that, the calibrated CERES-Maize model achieved a high degree of accuracy in replicating observed data for the tested varieties. Key performance indicators, including a d-index ranging from 0.75 to 0.98 and an nRMSE of 1.6–8.96% for traits such as days to anthesis, physiological maturity, grain yield, and total dry matter, confirmed the model's robustness. This evaluation successfully validates the CERES-Maize model as a reliable tool for simulating the phenology and productivity of these specific maize varieties under the diverse sowing conditions of Nigerian savannas.

Keywords: CERES-Maize, Model, Sowing, Window, Varieties, Agro-ecologies

INTRODUCTION

Crop simulation models (CSMs) are indispensable tools in modern agricultural research, enabling the prediction of crop growth, development, and yield in response to environmental and management factors. Among these, the CERES-Maize model within the Decision Support System for Agrotechnology Transfer (DSSAT) has been widely used to optimize management practices and assess production potential, thereby saving significant time and resources compared to tedious field trials (Adnan *et al.*, 2019; Kamara *et al.*, 2023). The reliability of these models, however, is contingent upon rigorous calibration and validation for specific crop genotypes under local soil and climatic conditions.

In Nigeria, maize is a crucial food security crop predominantly cultivated under rainfed conditions, making its productivity susceptible to climate variability and stress (Peter and Odjugo, 2010; Tofa *et al.*, 2021). To enhance resilience, research institutions like the International Institute of Tropical Agriculture (IITA) have developed improved, stress-tolerant varieties such as SAMMAZ-40. While the performance of such varieties has been tested in field trials, a comprehensive evaluation of their phenology and yield under diverse conditions through modeling remains limited. Previous modeling studies in the region have often focused on medium-maturing varieties (Tofa *et al.*, 2023), creating a knowledge gap regarding the model's accuracy for a wider range of genetic materials with differing maturity profiles.

Therefore, the primary objective of this study is to evaluate the performance of the CERES-Maize model for simulating the growth and yield of selected maize varieties in the Nigerian savannas. This research specifically focuses on validating the model for three distinct varieties (2016 TZdEE-Y, 2014 TZE-Y, and SAMMAZ-40) using experimental data collected across multiple sowing dates and locations. A successfully validated model will establish a reliable tool for future research and



decision-making, providing a foundation for subsequent investigations into optimal management strategies for these genotypes.

MATERIALS AND METHODS

Experimental Site

The study was conducted during the 2023 growing season at three locations within Kano State, Nigeria, representing two distinct agro-ecological zones. Two sites were located in the Sudan Savanna: the ICRISAT Research Farm at Bayero University Kano (11.299°N, 8.275°E) and Doka village in Tofa Local Government Area (LGA) (11.996°N, 8.292°E). The third site, Yaryasa village in Tudun-Wada LGA (11.299°N, 8.275°E), is situated in the Northern Guinea Savanna.

The Sudan Savanna is characterized by an annual rainfall of 550–850 mm and mean temperatures ranging from 25°C to 41°C. In contrast, the Northern Guinea Savanna receives higher average rainfall (approximately 1000 mm per annum) and has a milder temperature regime, with mean minimum and maximum temperatures of 20°C and 35°C, respectively. For the long-term model application, Doka and Yaryasa villages were selected as representative sites for the Sudan and Northern Guinea Savannas, respectively.

Field Experiments for Model Evaluation

A field experiment was established to evaluate six sowing dates, initiated on June 13 and repeated at weekly intervals until July 18. Three maize varieties with different maturity periods were tested: the extra-early-maturing 2016 TZdEE-Y, the early-maturing 2014 TZE-Y, and the medium-maturing SAMMAZ-40.

Experimental Design

The experiment employed a split-plot design with three replications at each site. Sowing dates were assigned as the main plot factor, and varieties were randomized as the subplot factor. Each subplot measured 3 m by 5 m, with a net harvest area of 6 m². Following land preparation involving glyphosate application, harrowing, and ridging, pre-treated seeds from IITA were sown at a density of 53,333 plants per hectare. Fertilizer was applied at a recommended rate of 120 kg N, 60 kg P₂O₅, and 60 kg K₂O per hectare in two splits. Weeds were controlled manually at 2 and 5 weeks after sowing (WAS), and the insecticide Ampligo was applied three times to manage fall armyworm infestations. Harvesting was conducted from the central rows upon physiological maturity.

Data Collection

Data collection encompassed soil properties, weather, crop growth, and yield components. Key phenological stages recorded included days to 50% anthesis and physiological maturity. At harvest, total dry matter (kg ha⁻¹) was determined from oven-dried plant samples. Grain yield was measured from sun-dried, shelled cobs and adjusted to a standard moisture content of 12% using the formula:

$$\text{Adjusted grain yield (kg ha}^{-1}\text{)} = [(\text{Grain yield per m}^2 \times 10,000) \times (100 - \text{mc})] / 88$$

Where mc is the measured grain moisture content.

For climate analysis, a 30-year historical baseline (1992–2022) was established. Future climate projections for the mid-century (2040–2069) and end-of-century (2070–2099) under RCP 4.5 and 8.5 were generated by applying delta factors from three Global Climate Models (GCMs) to this baseline, corresponding to projected CO₂ concentrations of 499 and 571 ppm, respectively.

Soil data

Prior to experimentation, a comprehensive soil characterization was performed at all sites. A 1.5-meter profile pit was excavated near each field, and the characteristics of the different soil horizons were described. Collected soil samples were air-dried, gently crushed, and passed through a 2-mm sieve to remove gravel and organic debris. A subsample was further ground to pass through a 60-micrometer sieve for detailed analysis.

The following key soil properties were determined using standard analytical procedures: Lower Limit (LL15), Drained Upper Limit (DUL), Saturated Water Content (SAT), Bulk Density (BD), Organic Carbon (OC), Total Nitrogen (N), Mehlich Available Phosphorus (P), particle size



distribution, and soil pH in water. These parameters were used directly for model initialization, validation, and long-term simulations.

Weather data

Meteorological data for model evaluation were collected in situ using WatchDog 2000 series automatic weather stations installed within a 20 km radius of each experimental site. The data recorded included daily minimum and maximum temperatures, daily rainfall, and daily solar radiation.

Model calibration

The CERES-Maize model applied in this study was initialized using pre-established genetic coefficients for the three maize varieties: 2016 TZdEE-Y, 2014 TZE-Y, and SAMMAZ-40. These coefficients, which define the specific growth and development parameters for each genotype, were sourced from the International Institute of Tropical Agriculture (IITA), thereby enabling the direct application of the model for simulation purposes without the need for further calibration.

Model validation

The validation of the CERES-Maize model was conducted by comparing its simulated outputs with empirical field data collected during the 2023 rainy season from the experimental sites at Tofa, BUK, and Tudun-Wada. This comparison is essential for verifying the model's capacity to accurately represent local crop performance (Abera *et al.*, 2018). The key validation parameters included days to 50% anthesis, days to physiological maturity, final grain yield, and total dry matter yield. The model's performance was quantitatively assessed using a suite of statistical indices, following established practices in model evaluation (Adnan *et al.*, 2020; Kamara *et al.*, 2023). These indices were: Root Mean Square Error (RMSE) and Normalized RMSE (nRMSE): These metrics quantify the average difference between simulated and observed values. The nRMSE, expressed as a percentage of the observed mean, provides a standardized measure of model error. According to the classification by Jamieson *et al.* (1991), an nRMSE of <10% is considered excellent, 10-20% is good, 20-30% is fair, and >30% is poor. Model Forecasting Efficiency (EF): This statistic ranges from -∞ to 1, where values closer to 1 indicate a model with high predictive skill and greater accuracy than simply using the observed mean. d-Statistic (Index of Agreement): Recommended by Willmott (1982), this is a bounded and standardized measure (0 to 1) of the degree of model prediction error, with a value of 1 indicating perfect agreement between simulated and observed data. It is particularly useful for cross-comparisons.

$$RMSE = \sqrt{1/N \sum (O_i - P_i)^2}$$

Where: P = predicted, O = observe, N = number of observations within each treatment.

$$nRMSE = \frac{RMSE \times 100}{\bar{O}}$$

\bar{O} is the overall mean of observed values

The simulation is considered excellent when the NRMSE is <10%, good if the NRMSE is >10% and <20%, fair if NRMSE is >20% and <30%, and poor if the NRMSE is >30% (Jamieson *et al.*, 1991).

$$EF = \frac{\sum_{i=1}^n (m_i - \bar{m})^2 - \sum_{i=1}^n (S_i - m_i)^2}{\sum_{i=1}^n (m_i - \bar{m})^2}$$

$$E = \frac{\sum_{i=1}^n (m_i - S_i)^2}{n}$$

Where n is the number of measured data set, S_i is the simulated data, m_i is the measured data, and \bar{m} is the mean of the measured data. The d statistic is recommended for making cross-comparisons when the d value is both relative and has bounded measures (Willmott 1982).

$$d = 1 - \frac{\sum_{i=1}^n (m_i - S_i)^2}{\sum_{i=1}^n (|S_i| + |m_i|)^2}$$

Where: $S_i = S_i - \bar{m}$ and $m_i = m_i - \bar{m}$

The graphical analysis, plotting simulated against observed data, was performed using Microsoft Excel 2016. The statistical indices were computed using the integrated Easy Grapher tool within the DSSAT v4.7 software suite (Yang and Huffman, 2004).



RESULTS

Description of Soil at the Evaluation Sites

The soil profile characteristics used for model application are summarized in Table 1. The result revealed a distinct physicochemical properties across the three experimental sites. At the BUK site, the soil exhibited a loamy sand texture in the surface horizon, characterized by a slightly acidic pH of 6.6. The volumetric water content at the lower limit (LL) was 0.553 mm/mm and at the drained upper limit (DUL) was 1.773 mm/mm. Saturation (SAT) and bulk density (BD) were 0.383 mm/mm and 1.582 g/cm³, respectively. The soil texture comprised 662 g/kg sand, 164 g/kg silt, and 174 g/kg clay. Nutrient analysis indicated low fertility levels, with total nitrogen (N) at 0.37 g kg⁻¹, available phosphorus (P) at 5.62 mg kg⁻¹, and organic carbon (OC) at 4.4 g kg⁻¹.

Conversely, the soils at Tudun Wada and Tofa were moderately acidic, both with a pH of 5.7. The Tudun Wada soil had a sandy texture with a composition of 700 g/kg sand, 127 g/kg silt, and 173.3 g/kg clay. Its water retention characteristics showed an LL of 0.108 cm³cm⁻³ and a DUL of 0.182 cm³cm⁻³, with SAT and BD values of 0.380 cm³cm⁻³ and 1.582 g/cm³, respectively. This site had a total N of 0.9 g/kg, available P of 26.67 mg kg⁻¹, and a low OC content of 0.3 g/kg. The Tofa's site soil was classified as silt-loam, with the highest sand content (720 g/kg) among the locations, along with 130 g/kg silt and 150 g/kg clay. Its LL and DUL were 0.118 cm³cm⁻³ and 0.191 cm³cm⁻³, respectively, with SAT and BD values identical to Tudun Wada. This site showed the lowest total N (0.13 g/kg) and OC (0.21 g/kg), while available P was 24.0 mg kg⁻¹. A comparative analysis of soil texture revealed that Tofa had the highest sand fraction, followed by BUK and Tudun Wada. For silt content, Tudun Wada ranked highest, followed by BUK and Tofa. Tudun Wada also possessed the highest clay content, whereas Tofa had the least.

Weather Conditions During the 2023 Cropping Season

The monthly weather data for the 2023 growing season at BUK, Tofa, and Tudun-Wada are presented in figure 1. The total seasonal rainfall varied across the sites, with BUK receiving the highest amount (785 mm), followed by Tofa (715 mm) and Tudun Wada (632 mm). The rainy season commenced in April and concluded in November at BUK, and in October at both Tofa and Tudun Wada. The peak rainfall month across all three locations was July, recording 226.3 mm at BUK, 222.1 mm at Tofa, and 151.5 mm at Tudun Wada. The lowest precipitation was observed in April at BUK (7.6 mm) and Tofa (18.4 mm), and in October at Tudun Wada (51.8 mm). The average minimum and maximum temperatures were 20.0°C and 31.3°C for both BUK and Tofa, while Tudun Wada experienced slightly higher averages of 22.1°C and 33.6°C, respectively. The average daily solar radiation was consistent across all locations at 19.5 MJ/m²/day.



Table 1: Physical and Chemical Properties of Soil Used for Model Validation (BUK, Tofa and T-Wada)

Horizon	Depth (cm)	LL (cm ³ cm ⁻³)	DUL (cm ³ cm ⁻³)	SAT (cm ³ cm ⁻³)	BD (g/cm ³)	OC (g kg ⁻¹)	Sand g kg ⁻¹	Silt g kg ⁻¹	Clay g kg ⁻¹	pH (1:2.5 H ₂ O)	N (g kg ⁻¹)	Meh P (mg kg ⁻¹)
BUK												
AP	0-28	0.100	0.201	0.401	1.56	0.44	680	120	200	6.6	0.4	5.62
AB	28-58	0.127	0.207	0.382	1.58	0.22	650	160	190	6.7	0.2	0.72
B1	58-120	0.112	0.194	0.385	1.57	0.21	660	180	160	5.9	0.2	0.17
B2	120-156	0.112	0.191	0.376	1.6	0.40	650	180	170	7.0	0.1	0.07
B3	156-210	0.102	0.180	0.376	1.6	0.40	670	180	150	6.1	0.1	0.72
Tudun Wada												
AP	0-26	0.107	0.188	0.391	1.55	0.42	710	150	140	5.8	0.04	2.7
B1	26-54	0.113	0.183	0.374	1.6	0.27	730	110	160	5.5	0.02	2.1
B2	54-95	0.099	0.164	0.368	1.62	0.11	750	110	140	5.6	0.01	13.2
BC	95-126	0.116	0.195	0.388	1.56	0.35	690	150	160	5.7	0.02	8.7
Tofa												
AP	0-13	0.094	0.167	0.384	1.57	0.31	750	130	120	5.4	0.03	4.7
BT1	13-36	0.101	0.167	0.371	1.61	0.18	750	110	140	5.4	0.02	2.4
BT2	36-64	0.12	0.188	0.371	1.61	0.15	710	110	180	5.6	0.02	0.4
BT3	64-110	0.133	0.216	0.384	1.57	0.25	630	170	200	6.2	0.02	12.5
BT4	110-154	0.142	0.211	0.374	1.6	0.23	690	90	220	6.0	0.02	0.4
BT5	154-220	0.12	0.197	0.379	1.59	0.16	670	150	180	5.8	0.02	3.6

LL15=lower limit at 15barometric pressure, DUL=drained upper limit, SAT: volumetric water content at saturation, BD=bulk density, OC=organic carbon content, N= Total nitrogen and Meh P=Mehlich Available Phosphorus

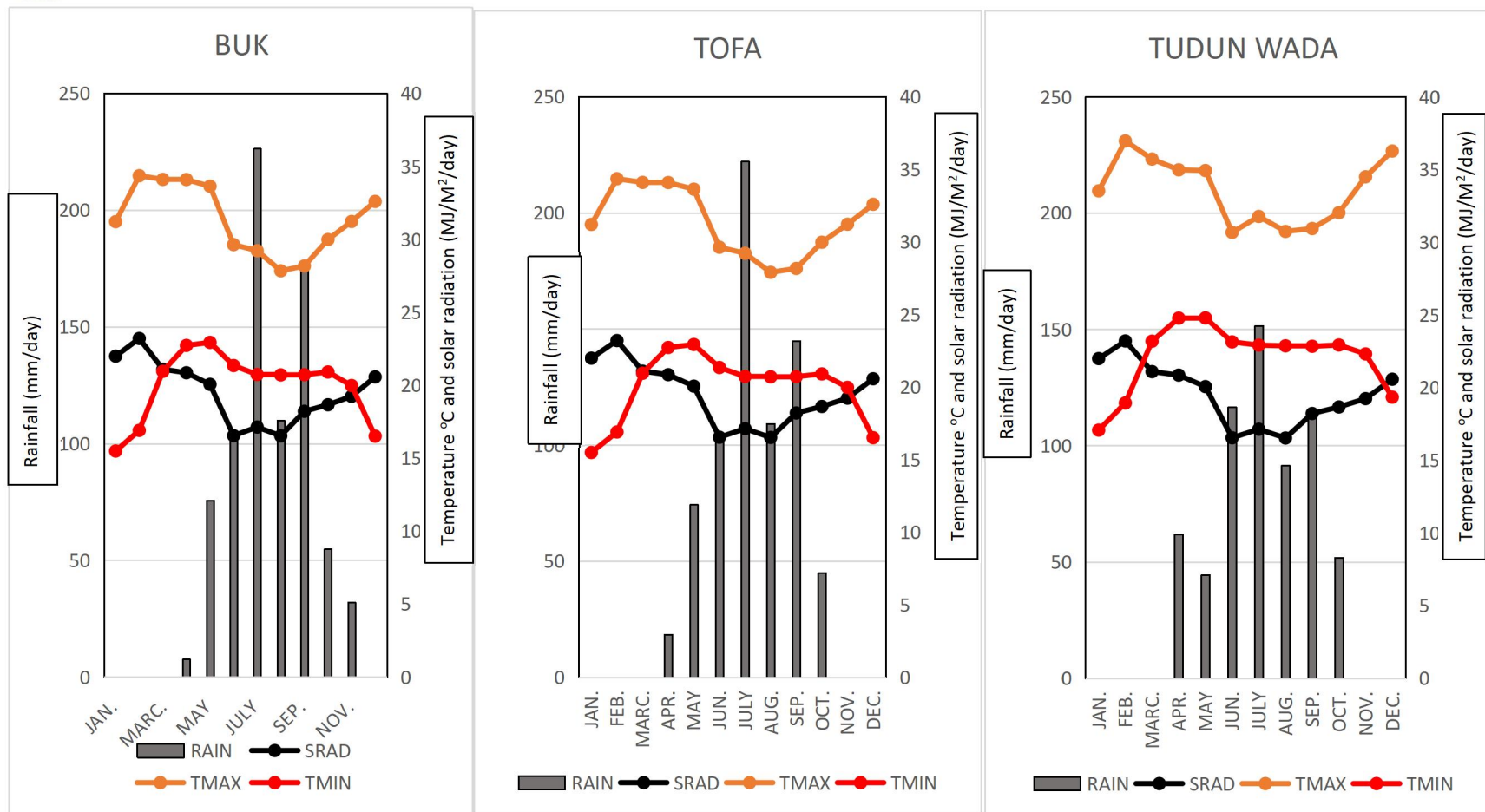


Figure 1: Monthly rainfall, minimum temperature (Tmin), maximum temperature (Tmax) and solar radiation (SRAD) at BUK, Tofa and Tudun Wada for 2023 experimental year.



CERES-Maize Model Evaluation

Figures 2, 3 and 4 shows the predictive accuracy of the CERES-Maize model, utilizing the genetic coefficients developed by IITA, was rigorously evaluated against independent field data collected during the 2023 cropping season. The evaluation dataset comprised six sowing windows at both the BUK and Tudun Wada sites, and five sowing windows at the Tofa site. Model performance was assessed by comparing simulated versus observed values for four critical parameters: days to 50% anthesis, days to physiological maturity, grain yield, and total above-ground dry matter.

Predictive Accuracy for Phenological Development

The model demonstrated a high degree of accuracy in simulating the phenological development of the maize varieties. The results, detailed in Table 3, revealed a variety-specific performance. Early-Maturing Varieties (2016 TZdEE-Y and 2014 TZE-Y): For these genotypes, the model's simulation of days to anthesis and physiological maturity was excellent. The normalized Root Mean Square Error (nRMSE) was consistently below 3%, with an absolute RMSE of only 2-3 days, indicating very minor deviations from observed values. This high precision is further supported by a d-index (index of agreement) ranging from 0.92 to 0.98, reflecting near-perfect agreement, and a modeling efficiency (EF) of 0.56 to 0.91, confirming that the model predictions are substantially better than using the observed mean.

Medium-Maturing Variety (SAMMAZ-40): The model also provided reliable predictions for SAMMAZ-40, though with slightly higher error margins than the early-maturing varieties. The nRMSE for phenological stages remained below 5%, with an RMSE of 3-5 days. The d-index values of 0.81 to 0.84 still indicate a strong agreement between simulated and observed data. However, the forecasting efficiency (EF) was weaker for this variety, ranging from 0.34 to 0.38, suggesting that while the model is accurate, its predictive skill for SAMMAZ-40's development timeline is moderately lower.

Predictive Accuracy for Yield and Biomass

The model's performance in simulating grain yield and total dry matter was assessed as more than adequate for all varieties, confirming its utility for productivity forecasting. Grain Yield: Simulations for final grain yield were robust across all three genotypes. The RMSE values ranged from 236.05 to 364.33 kg ha⁻¹. Most importantly, the nRMSE was consistently below the 10% threshold, which is widely classified as an excellent level of model performance. This indicates a high level of precision in predicting yield outcomes across the different sowing dates and locations.

Total Dry Matter (Biomass): The model performed well in simulating above-ground biomass accumulation. Notably, the medium-maturing SAMMAZ-40 showed the lowest absolute error for this trait, with an RMSE of 712.62 kg ha⁻¹ and a d-index of 0.81, pointing to a reliable estimation of total biomass production.

Graphical Analysis and Comparative Performance

The relationship between simulated and observed values for all parameters across sowing windows and locations is visualized in Figures 2, 3, and 4. These graphs showed the data points closely distributed along the 1:1 line, providing a visual confirmation of the model's strong predictive capability. The scatter plots also illustrate the prediction deviation for each specific treatment combination, allowing for a detailed assessment of any systematic biases.

A comparative analysis of the three varieties revealed that 2014 TZE-Y consistently exhibited the highest model efficiency across all evaluated parameters, with superior d-index and EF values compared to both SAMMAZ-40 and 2016 TZdEE-Y. This suggests that the model and its genetic coefficients are particularly well-tuned for simulating the growth and development of this early-maturing variety under the tested conditions.

In summary, the evaluation confirms that the calibrated CERES-Maize model is a highly accurate and reliable tool for simulating the phenology, yield, and biomass of the studied maize varieties in the savanna agro-ecologies of Nigeria. Its strong performance provides confidence for its application in subsequent long-term climate impact and adaptation studies.

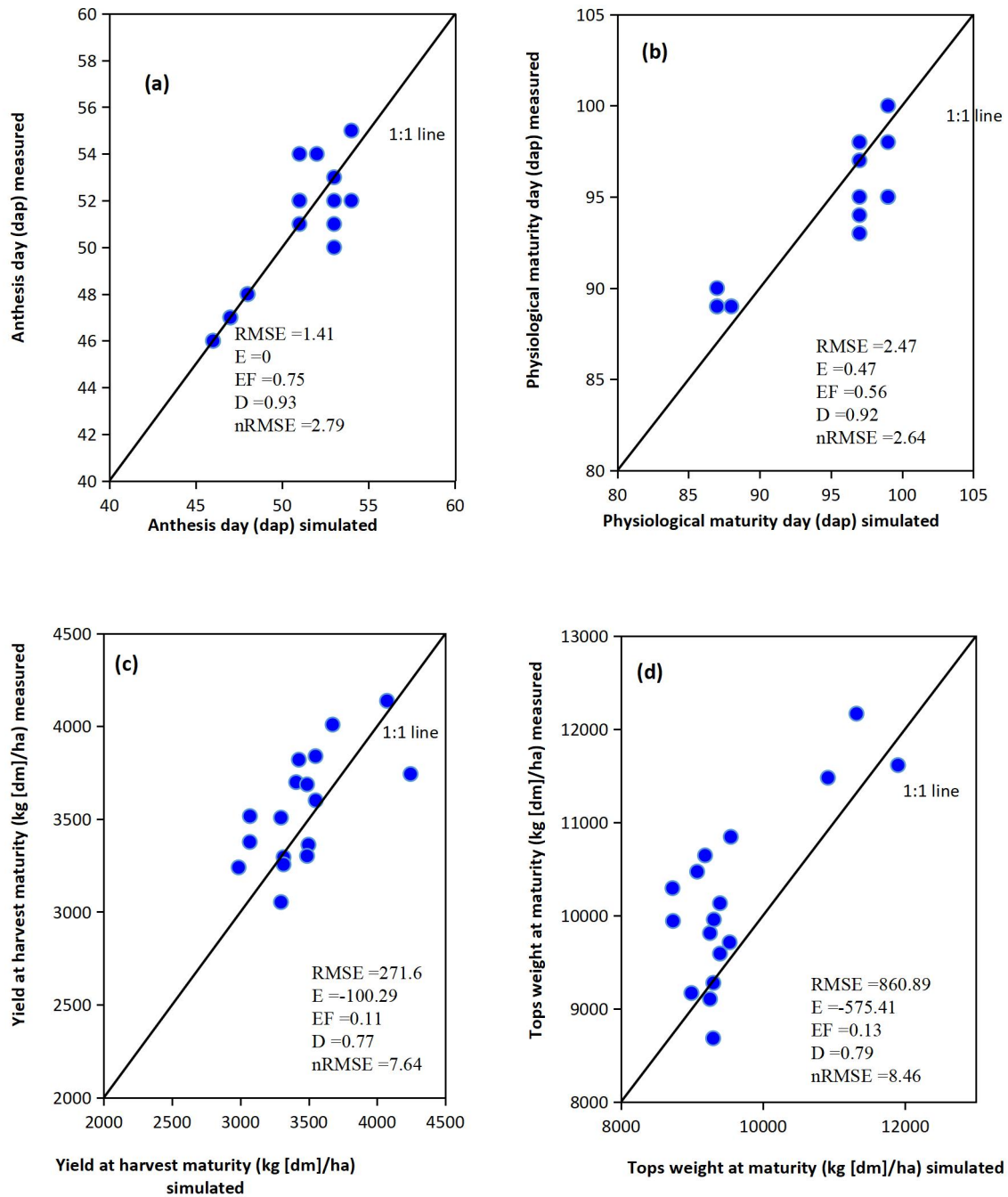


Figure 2. Comparison of simulated (S) and observed (O) days to anthesis (a), days to physiological maturity (b), grain yield at maturity (c) and shoot dry matter at maturity (d) for 2016 TZdEE-Y using BUK, Tofa and Tudun wada experimental data sets.

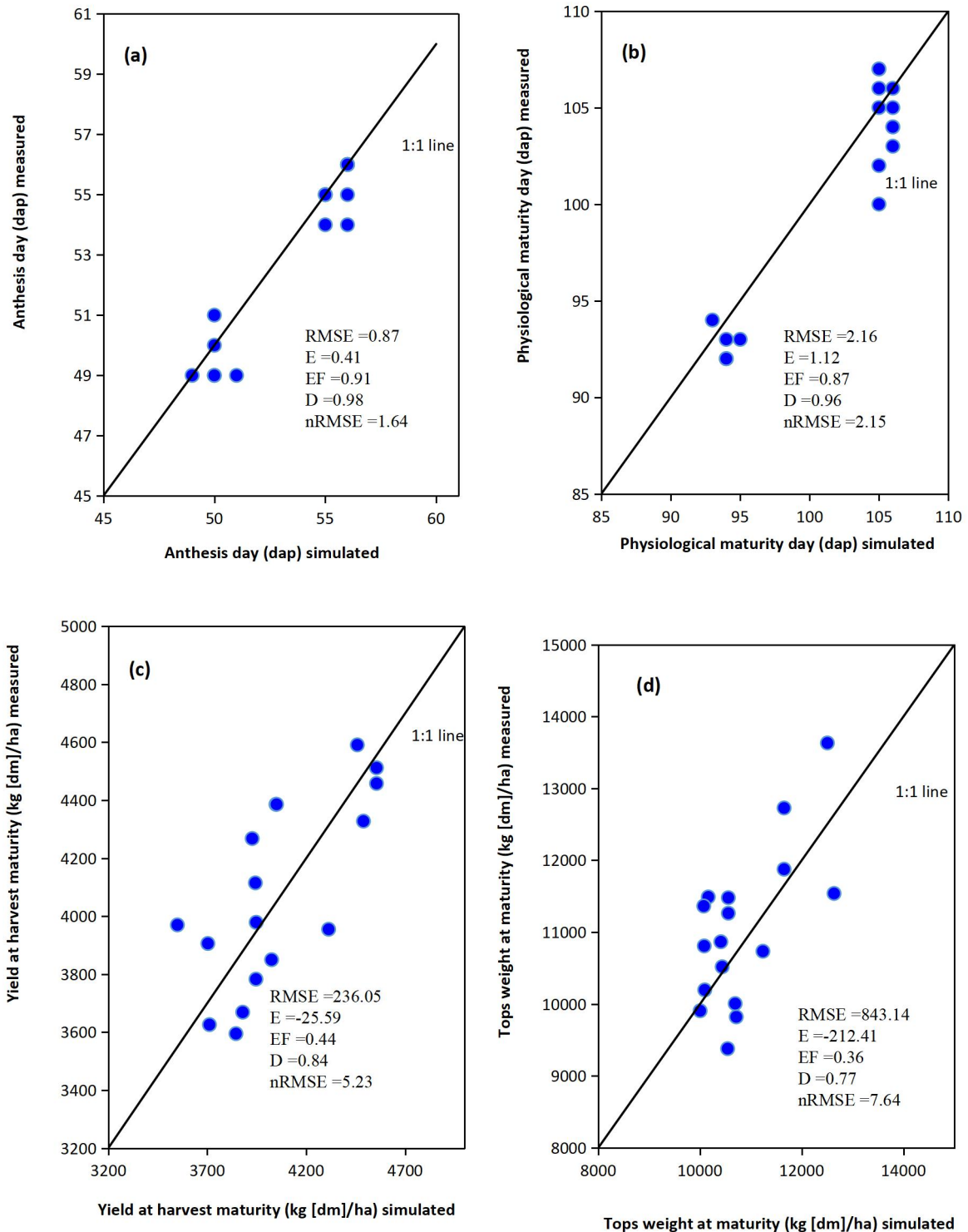


Figure 3. Comparison of simulated (S) and observed (O) days to anthesis (a), days to physiological maturity (b), grain yield at maturity (c) and shoot dry matter at maturity (d) for 2014 TZE-Y using BUK, Tofa and Tudun wada experimental data sets.

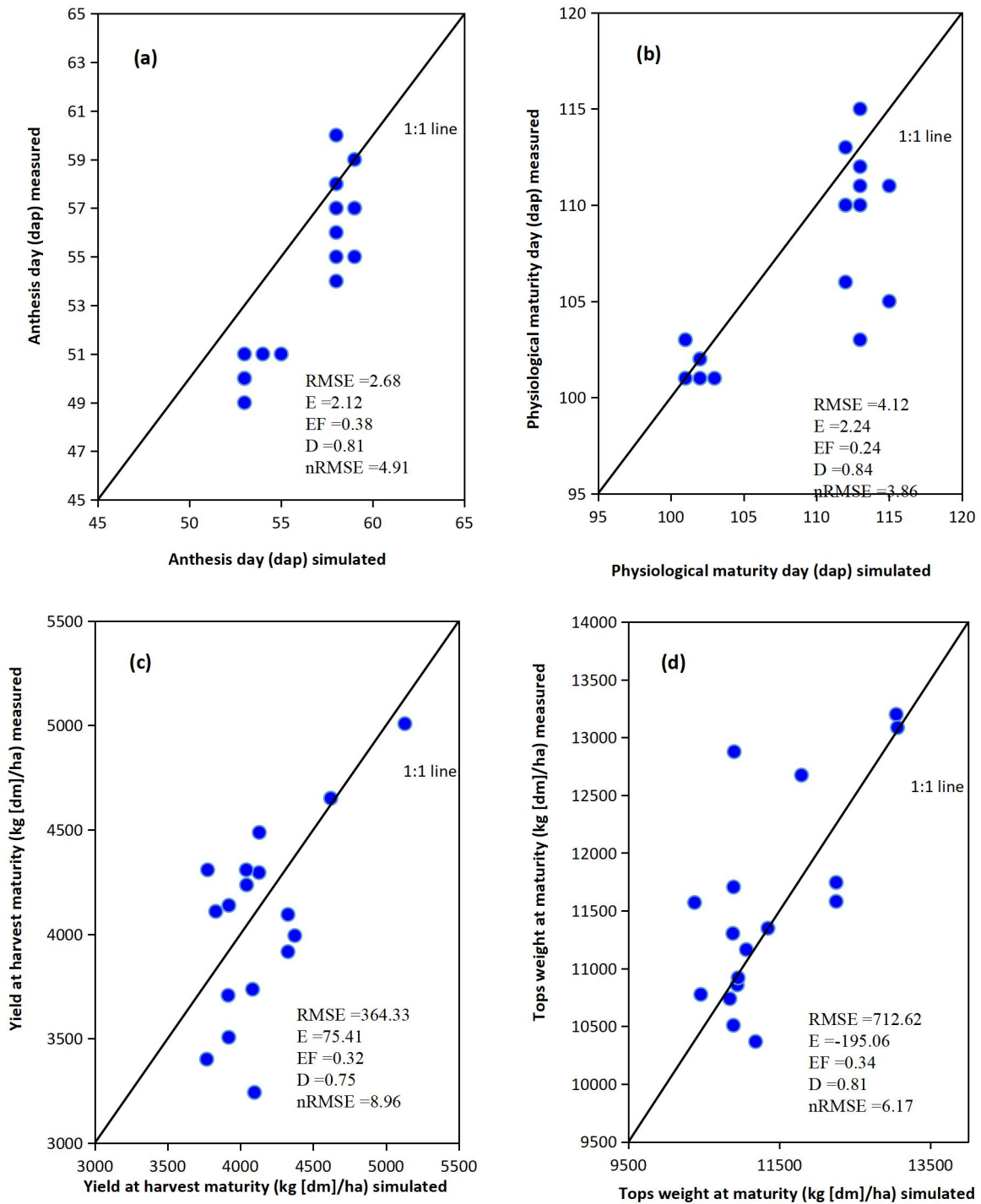


Figure 4. Comparison of simulated and measured days to anthesis (a), days to physiological maturity (b), grain yield at maturity (c) and shoot dry matter at maturity (d) for SAMMAS-40 using BUK, Tofa and Tudun wada experimental data sets.



DISCUSSION

The evaluation demonstrates that the CERES-Maize model, calibrated with genetic coefficients from IITA, achieved strong predictive performance for maize phenology and yield in the Nigerian savannas, aligning with previous local studies. The model accurately simulated days to anthesis and physiological maturity for early-maturing varieties (2016 TZdEE-Y and 2014 TZE-Y), showing minimal deviation from observed values (nRMSE < 3%, RMSE 2-3 days). These findings are consistent with research by Tofa *et al.* (2021), who reported successful simulation of crop phenology using the DSSAT framework. The high d-index values (0.92-0.98) further confirm the model's reliability in replicating crop development patterns observed in the region, a level of accuracy corroborated by Adnan *et al.* (2019), who also found high d-index values (0.93-0.98) for phenology and yield in similar agro-ecologies. This supports the model's application for agricultural decision-making in northern Nigeria.

Varietal differences in model performance were apparent, with the medium-maturing SAMMAZ-40 showing slightly higher prediction errors (nRMSE < 5%, RMSE 3-5 days) and lower forecasting efficiency (EF 0.34-0.38) compared to early-maturing varieties. This pattern echoes observations by Kamara *et al.* (2023) in the Northern Guinea Savanna, where model accuracy varied among maize genotypes with different maturity periods. The consistent superiority of 2014 TZE-Y across all parameters suggests its genetic coefficients were particularly well-calibrated for local conditions, possibly reflecting more extensive prior evaluation of early-maturing varieties as noted by Adnan *et al.* (2019). This is supported by the work of Adnan *et al.* (2019), who successfully determined genetic coefficients for ten new maize varieties, demonstrating a reliable methodology for varietal calibration that can explain the performance differences observed.

For yield parameters, the model demonstrated robust performance with grain yield nRMSE consistently below 10% across all varieties, meeting the threshold for excellent model performance established in Nigerian agricultural research. The reliable simulation of total dry matter, particularly for SAMMAZ-40 which showed the lowest biomass error (RMSE 712.62 kg ha⁻¹), reinforces the model's utility for productivity forecasting under local conditions, a finding consistent with Adnan *et al.* (2017) who reported accurate predictions of yield, harvest index, and biomass. These results validate the approach used by Tofa *et al.* (2020) and Beah *et al.* (2021), who effectively deployed the CERES-Maize and APSIM models to evaluate optimal sowing dates and variety combinations across the savannas. Furthermore, the model's robustness extends to nutrient management, a critical aspect for smallholder farming systems in Nigeria. This capability is corroborated by research in Kano State, where Kamara *et al.* (2023) successfully employed the CERES-Maize model to determine site-specific agronomic optimum nitrogen rates, demonstrating its accuracy in simulating growth, yield, and soil nitrogen dynamics under different fertilizer management practices. The model's proficiency in capturing the complex interactions between genotype, environment, and management (GxExM) allows it to reliably evaluate integrated strategies. For instance, the work of Tofa *et al.* (2021) in the Northern Guinea Savanna showed that combining adjusted sowing dates with improved nutrient management, as simulated by the model, could significantly enhance maize productivity and resilience. This consistent performance across diverse studies confirms the model's utility as a decisive tool for developing tailored nutrient management recommendations for farmers in the Nigerian savannas.

The successful validation provides confidence for deploying the model in climate impact studies and adaptation planning across Nigeria's savanna agro-ecologies, supporting evidence-based agricultural policy and farmer decision-making in the face of climate variability.

CONCLUSION AND RECOMMENDATION

Based on the successful validation of the CERES-Maize model for simulating the phenology and yield of key maize varieties in the Nigerian savannas, it is concluded that the model is a highly reliable tool for evaluating and optimizing agronomic strategies in the region. It is therefore recommended that policymakers and agricultural extension services utilize this validated model to develop and disseminate integrated climate-smart packages for smallholder farmers, promoting the



use of well-calibrated varieties across different maturity groups alongside precise, location-specific sowing date recommendations to enhance resilience and productivity in the face of climate variability.

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