



Evaluation and application of the CROPGRO – Cowpea model for simulating appropriate sowing window and planting density of cowpea varieties across contrasting environments

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ABSTRACT

Context: Cowpea [*Vigna unguiculata* (L.) Walp.] is an important legume crop in sub-Saharan Africa where its grain and fodder are valued for food and feed. Grain yields are, however, low due to several biotic and abiotic constraints. Several improved stress-tolerant varieties and complementary agronomic management technologies have been developed to enhance its productivity and sustainability. Cropping simulation models are useful tools for evaluating the deployment of crop varieties and management options for target locations. While the CSM-CROPGRO model in DSSAT has been used to simulate the performance of several legume crops, only a few studies have evaluated and used the relatively new CSM-CROPGRO-cowpea model for use in West Africa.

Objectives: The objectives of this study were to (i) evaluate the performance of the CSM-CROPGRO-Cowpea model in simulating the cowpea growth and yields in contrasting environments (ii) use the model to assess the optimal sowing window and planting density of cowpea varieties across contrasting environments in the savannas of Nigeria.

Methods: Here, we used comprehensive savanna-wide datasets to calibrate and validate the CSM-CROPGRO-cowpea model for savannah environments. The evaluated model was then applied to assess the yield performance of cowpea varieties with varying plant densities and six sowing windows across four sites considering 36 growing seasons.

Results: The model accurately simulated cowpea phenology (RMSE 0.58–0.67 day; nRMSE 1.36–1.46 %; d-index > 0.90 for days to flowering, RMSE 0.82–1.73 days; nRMSE 1.09–2.29 %; d-index 0.88–0.99 for days to physiological maturity), grain yield (RMSE 86–121 kg ha⁻¹; nRMSE 3.66–6.14 %; d-index > 0.90) and total dry matter (RMSE 260–295 kg ha⁻¹; nRMSE 4.79–10.73 %; d-index = 0.87–0.95). The long-term simulation results indicate that SAMPEA 9 showed no response to sowing density beyond 13.3 plants m⁻² across all locations, likely due to interplant competition at higher densities. In contrast, the simulated yield of SAMPEA 14 and FUAMPEA 1 increased as plant density increases from 13.3 to 40 plants m⁻². In northern Guinea savanna, sowing could be delayed until July 14 at Demsa and July 29 at Zaria for all tested varieties. In the Sudan savanna AEZ (SS), sowing should be done between July 1 and 14 for all varieties, beyond which there will be a significant reduction in yield.

Conclusion: Except for SAMPEA 9, the simulated optimum planting density for all the varieties is 40 plants m⁻² in all AEZ, while the sowing window was dependent on location and AEZ. The variety SAMPEA 9 was the most yield-stable variety across the tested environments and did not require planting density above the current

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industry recommendations of 13.3 plants m⁻². This study could fill the knowledge gap in understanding optimal cowpea management opportunities needed to maximize productivity and strengthen cropping resilience.

1. Introduction

Cowpea [*Vigna unguiculata* (L.) Walp.] is an important crop that plays a key role in the food and nutritional security and livelihood of millions of people in most parts of Africa (El Naim and Abereldar, 2010; Ajeigbe et al., 2005). More than 90 % of the world's cowpeas are grown in sub-Saharan Africa, most of which (83 %) are in West Africa (Nurudeen et al., 2018). Some eight million ha of cowpea are grown in West and Central Africa (WCA), with Nigeria accounting for 4.7 million ha (36 % of total production in WCA), producing over 3.6 million tons (60 % of the world's total) annually (FAOSTAT, 2022). In Nigeria, cowpea is widely grown in the Guinea and Sudan savanna agroecological zones. Despite the importance of the crop in West Africa, the grain yield is very low (<1 t ha⁻¹) despite considerable large yield potential and wide adaptation of the crop to this environment (Anago et al., 2021; FAOSTAT, 2022). This also applies to Nigeria, where the average yield ranges from 0.6–0.7 t ha⁻¹ (FAO, 2020). The low yield is attributed to severe pest and disease complex interactions with the crop, poor soil fertility, drought, and suboptimal crop management practices (Ajeigbe et al., 2010).

Over the years, national and international agricultural research institutions have released and disseminated several cowpea varieties that are resistant to predominant diseases and parasitic weeds such as *Striga gesneroides* and are tolerant to drought (Kamara et al., 2018). Evaluation of these new varieties under on-station and researcher-managed plots has indicated a high yield potential of the new varieties. For example, grain yields ranging from 1.3 to 2.2 t ha⁻¹ have been reported in sole cowpea cropping systems, whereas grain yields of up to 1.2 t ha⁻¹ have been reported in intercropping systems in the savannas of Nigeria using the improved varieties (Omoigui et al., 2023). This substantial yield gain over average farmers' yields (0.7 t ha⁻¹) in Nigeria shows that there is scope to close the yield gap if appropriate agronomic practices are adopted. Thus, evaluating agronomic practices that could enhance crop yields is vital. Using optimal plant densities and appropriate sowing windows may increase cowpea productivity (Kamara et al., 2016).

The increased inter-seasonal variations in the onset and cessation of rainfall in Nigeria (Tofa et al., 2020; Mkuhlani et al., 2024), and in-season dry spells (Adnan et al., 2017) make the determination of an appropriate sowing window a relevant topic for rainfed crop production. This is particularly important for cowpea, which is generally cultivated as rainfed and planted in the middle of the season. Cowpea is usually planted between July and August in the Nigeria savannas to avoid or minimize insect pest attacks and the negative effect of photosensitivity on the crop when planted early in the onset of growing season (Kamara et al., 2007). Early planting in the season could also result in poor grain quality if it matures in the middle of the season. On the other hand, planting too late may be risky because if the rains cease early, the quantity and quality of cowpea grains produced may be reduced (Isubikalu et al., 1999). The instability in rainfall has created uncertainty in establishing appropriate sowing windows for cowpea.

Plant density is another important contributor to the grain yield of field crops such as cowpea and soybean. Optimum plant density may vary with location and variety (Kamara et al., 2016). According to Liu et al. (2008), crop cultivars respond differently to high plant density because of differences in growth habits. The recommended planting density of 133,333 plants ha⁻¹, may not be sufficient for optimal cowpea yield, especially for the erect and semi-erect varieties. This population recommendation does not consider varietal requirements. The low density resulting from wide spacing usually leads to low yields in cowpea (Kamara et al., 2016). High plant density increases dry matter accumulation and grain yield (Bruns, 2011).

While many disease-resistant and drought-tolerant cowpea varieties along with improved crop management technologies have been developed or identified for deployment to farmers, the performance of these varieties and their response to yield-increasing crop management technologies such as plant density and sowing window have not been evaluated for most of the areas across the cowpea growing regions in northern Nigeria. The evaluation of the performance of these technologies would require time-consuming and expensive field experiments across the regions (Tofa et al., 2020). The results of field evaluations of crop technologies cannot be extrapolated to other locations or regions because of considerable variability in soils and climate conditions outside the areas where the technologies have been tested (Tovihoudji et al., 2019).

The use of decision support tools such as the Decision Support System for Agro-technology Transfer (DSSAT) could assist in scaling cowpea technologies in a timely and cost-effective manner. It could help in decision-making in site selection and evaluation of various management options, including the selection of appropriate varieties and extrapolation and scaling-out of results (Tovihoudji et al., 2019). DSSAT and its crop simulation models have been used for a wide range of applications at different spatial and temporal scales in tropical environments (Hoogenboom et al., 2019).

In Nigeria, the DSSAT CROPGRO-Soybean model has been calibrated and used to accurately simulate the growth and yield of soybean under a range of crop management practices in several locations (Bebeley et al., 2022; Kamara et al., 2023). The CROPGRO model has also been used to simulate the performance of other leguminous crops such as groundnut (Naab et al., 2015; Halder et al., 2017; Halder et al., 2015; Pandey et al., 2001), chickpea (Mohammed et al., 2017), canola (Qian et al., 2017) in many countries. However, so far only a few studies have been conducted with the CROPGRO-Cowpea model. This includes planting date evaluation in Bahia, Brazil (Filho et al., 2013), irrigation management in Piauí State, Brazil (Bastos et al., 2002), and nitrogen management in Sudan (Lomeling et al., 2014; Lomeling and Huria, 2019, 2020). The CROPGRO-Cowpea model is relatively new and would benefit from further evaluation in other regions and environments (Filho et al., 2013), particularly in West Africa, where the crop is primarily grown. The objectives of this study were to: i) calibrate the CROPGRO model for three cowpea varieties in the savannas of Nigeria, ii) use independent data sets to evaluate the model for these varieties, and iii) use the calibrated model to simulate the interactive effects of sowing window and planting density on the grain yield of the cowpea varieties.

2. Materials and methods

2.1. Study locations

Field experiments were conducted at the research farm of Bayero University Kano (BUK) from 2016 to 2018, at Audu Bako College of Agriculture (ABCOA), Dambatta from 2016 to 2020 and at the IITA Research farm Shika, Zaria in 2020, all in Nigeria to generate data for the calibration of the CROPGRO-cowpea model. Both the BUK, Kano Research farm (11.516°N, 8.516°E, 466 m a.s.l.) and ABCOA, Dambatta farm (12.333°N, 8.517°E, 442 m a.s.l.) are in the Sudan savanna (SS) agroecological zone (AEZ) (Fig. 1), and have monomodal rainfall patterns. They experience a long dry season and a rainy season extending from June to October, with average minimum and maximum temperatures of 20.2°C and 33.9°C (Tofa et al., 2023), and rainfall ranging from 600 to 800 mm annually (Adnan et al., 2017). The site at Zaria (11.187°N, 7.147°E, 702 m a.s.l.) located in the Northern Guinea savanna (NGS) AEZ, also experiences a monomodal rainfall pattern. It has a longer

growing season lasting 151–180 days and receives an annual rainfall of 900–1000 mm (Jagtap, 1995) with average minimum and maximum temperatures of 19.3°C and 31.9°C (Tofa et al., 2023). The soils of these agroecological zones are classified as Typic Haplustalf according to USDA soil taxonomy (USDA, 1981). The soils are porous, well drained, with a higher proportion of sand (>45 %), and considered to be fragile (Ogunwole et al., 2001; Shehu et al., 2015).

Model evaluation experiments were conducted at Abuja (9.076° N, 7.399° E, 476 m a.s.l) in the southern Guinea savanna (SGS) AEZ and Zaria from 2016 to 2018 (Fig. 1). The site for model evaluation is in the same location used for model calibration at Zaria. Abuja is characterized by a growing season lasting 181–210 days (Ayanlade et al., 2013) and receives a total annual rainfall ranging from 1000 to 1524 mm (Ayanlade et al., 2013; Omotosho et al., 2013). The average maximum temperature reaches around 33°C while the minimum temperature is about 21.4°C (Ayanlade et al., 2013; Omotosho et al., 2013). In Abuja, the soils are classified as Alfisols, sub-order of Ustalfs with a Ustic moisture regime.

For the application of the model in the main cowpea-growing areas of northern Nigeria, two contrasting environments within the NGS and SS AEZs were considered. Two locations were selected in the northeast (one per AEZ) and two in the northwest (one per AEZ). The locations in the northeast are Demsa (NGS AEZ) (9° 17' 46.4928" N, 12° 9' 0.2484" E, 246 m a.s.l) and Puba Vidau (SS AEZ) (9° 17' 46.4928" N, 12° 23' 21.7428" E, 161 m a.s.l) while in the northwest Zaria (NGS) and BUK-Kano (SS) (Fig. 1) were selected.

2.2. Field experiments for model calibration and evaluation

The calibration trial involved nine field experiments conducted during the rainy season (June to October) in three locations from 2016 to 2021. Three varieties with contrasting durations for maturity (early maturing–FUAMPEA 1, medium–maturing–SAMPEA 14, and late–maturing– SAMPEA 9) were used. The experiments were established at BUK-Kano on the 25th of July each year in 2016, 2017, and 2018 and at ABCOA, Dambatta on the 24th of July in 2016, 25th of July in 2017 and 2019, 10th of August in 2020 and 27th of July in 2021. At

Zaria, the experiments were established on 7th August 2020. The varieties were arranged in a randomized complete block design in each site and year with three replications. The experiments were conducted under optimum management practices to avoid weed competition, water and nutrient stress. Poultry manure at the rate of 4 t ha⁻¹ was applied to the plots at land preparation before sowing. Each plot has four rows of 5 m in length at a row spacing of 0.75 m between them, while the cowpea seeds were sown on the ridges 25 cm apart to give a target plant population of 133,333 plants ha⁻¹. Phosphorous (P) and potassium (K) were applied at 40 kg ha⁻¹ P₂O₅ and K₂O, respectively. The P was applied in the form of Triple Super Phosphate (TSP) while K was applied in the form of Muriate of Potash (MOP). Immediately after sowing, a mixture of Pendilin (500 g L⁻¹ pendimethalin; Meghmani Industries Limited, India) at a rate of 1.0 L ha⁻¹ was applied, followed by hand weeding three weeks later to control weeds. The plants were sprayed with the insecticide Karate (50 g L⁻¹ lambda-cyhalothrin; Syngenta Crop Protection AG, Basel, Switzerland) at a rate of 1.0 L ha⁻¹ when the first few insects were noticed at the vegetative, flowering, and podding stages. The spraying was done weekly until the end of the podding stage.

For model evaluation, six sowing date experiments were established during the cropping seasons (July–November) of 2016, 2017, and 2018 at Abuja and Zaria. The sowing dates were selected to reflect the planting period of cowpea in the Nigeria savannas. Farmers start planting in first week of July until third week of August. In each location the three varieties for which the model was calibrated (SAMPEA 14, FUAMPEA 1 and SAMPEA 9) and six sowing dates (except in 2016 at

Table 1
Sowing dates for Model evaluation experiment at Abuja and Zaria.

Location	Year	Sowing Dates
Abuja	2016	10th, 17th, 24th, 31st August; 7th September
Abuja	2017	12th, 19th, 26th August; 3rd, 10th, 17th September
Abuja	2018	6th, 13th, 20th, 27th August; 4th, 11th September
Zaria	2016	28th July; 5th, 12th, 19th, 26th August; 3rd September
Zaria	2017	28th July; 5th, 12th, 19th, 26th August; 3rd September
Zaria	2018	28th July; 5th, 12th, 19th, 26th August; 3rd September

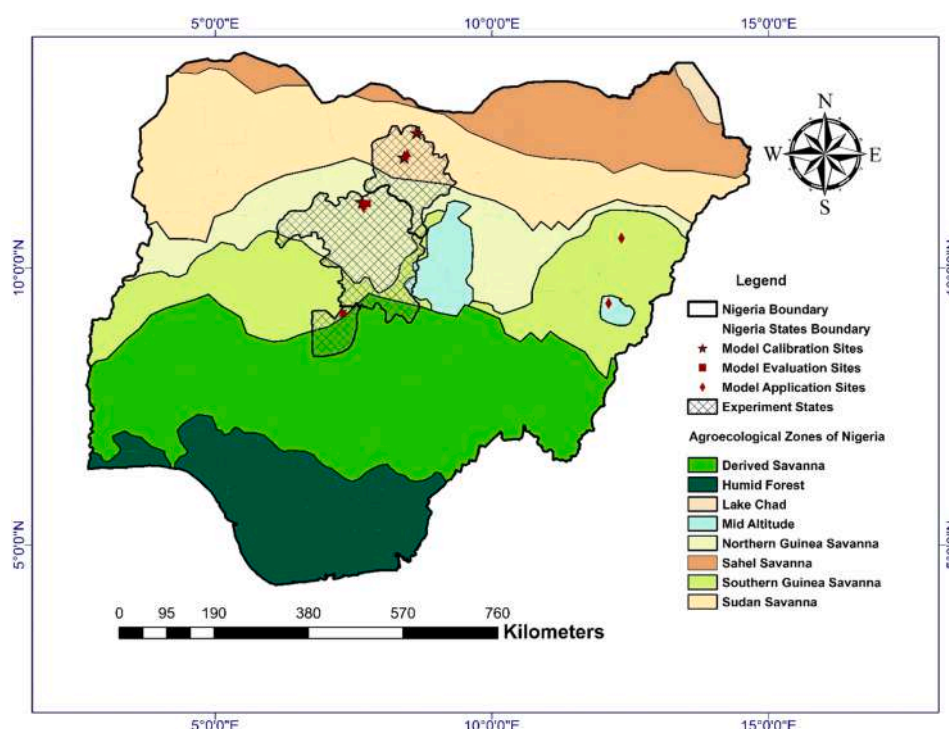


Fig. 1. Map of the study area showing agroecological zones boundaries and sites of model simulations.

Abuja where there were 5 sowing dates) were used as treatments. The treatments were arranged in split plots design with sowing date assigned to the main plot and the varieties to the subplot. The sowing dates for both locations are presented in Table 1. Sowing, fertilizer and weed control procedures were the same as described for the calibration experiment

2.3. Plant measurements

The parameters measured were number of days to 50 % flowering, and 95 % physiological maturity, final total dry matter yield (kg ha^{-1}), and final grain yield (kg ha^{-1}). The number of days to 50 % flowering and 95 % physiological maturity were determined from plants in the two middle rows. The total dry matter yield was measured at maturity using a 1.5 m² quadrat placed at the centre of the two middle rows. All cowpea plants within the quadrat were cut at the base and separated into leaves, stems, and pods. The three parts of the crop were sun dried until a constant weight was achieved, then weighed separately and summed to obtain final total dry matter for each plot. Remaining pods from the two middle rows were harvested, dried, threshed, and their grains weighed. Final grain yield per plot was estimated by combining the yield from the quadrat with that of the remaining net plot. The final yield was adjusted to 12 % moisture content and expressed in kg ha^{-1} .

2.4. Weather conditions at study sites

The WatchDog 2000 series weather station (Spectrum Technologies Inc, USA) was used to monitor daily weather conditions (rainfall, minimum and maximum air temperature, and solar radiation) at the calibration and evaluation experimental sites. Every 30 minutes, the stations automatically measure and log the total amount of rain, minimum and maximum air temperatures, and solar radiation. These readings were converted to daily formats as required in the weather data file of DSSAT, and were used as input files in the model calibration and evaluation processes. Table 2 shows a summary of the average weather data used for the calibration and evaluation sites.

Long-term weather data spanning from 1987 to 2022 for the four selected model application sites were sourced and downloaded from gridded Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for daily rainfall (Funk et al., 2015) and National Aeronautics and Space Administration (NASA) database for Climatology Resource for Agroclimatology <http://power.larc.nasa.gov/> for minimum and maximum air temperature and solar radiation. Thereafter, these datasets

Table 2
Weather data at model calibration and evaluation sites in the savannas of Nigeria.

Location	Year	Total Rainfall (mm)	Min Temperature (°C)	Max Temperature (°C)	Avg. Solar Radiation ($\text{MJ m}^{-2} \text{day}^{-1}$)
BUK (Kano)	Calibration				
	2016	648	21.3	33.9	18.0
	2017	643	20.4	33.4	24.9
Dambatta	2018	686	14.1	32.9	29.0
	2016	794	20.4	34.4	22.2
	2017	708	19.5	35.7	21.8
	2018	606	19.1	35.0	21.8
	2020	723	19.0	34.3	20.8
Abuja	2021	514	18.6	35.1	20.5
	Evaluation				
	2016	1516	21.4	33.3	17.6
	2017	1134	21.1	33.2	21.2
	2018	1467	21.1	32.6	17.0
Zaria	2018	789	18.7	32.3	20.8
	2019	870	19.4	32.2	21.1
	2020	950	19.2	31.8	20.9

were merged using R scripts and transform them into a format suitable for use in the DSSAT model. The data reveal significant variations in average precipitation and temperature over the 36-year period among the locations (Fig. 2). The seasonal rainfall was 945 mm in Demsa and 1049 mm, in Zaria both in the NGS AEZ. Average seasonal minimum and maximum temperatures were 21.8 and 33.4°C for Demsa, and 18.4 and 30.4°C for Zaria. Seasonal rainfall was 874 mm at BUK (Kano) and 1049 mm, at Puba Vidau in the SS AEZ. The average seasonal minimum and maximum temperatures were 19.1 and 33.2°C for BUK (Kano), and 20.5 and 33.0°C for Puba Vidau. Solar radiation was 21.1 $\text{MJ m}^{-2} \text{days}^{-1}$ in both Kano and Puba Vidau, and 20.5 and 20.9 $\text{MJ m}^{-2} \text{day}^{-1}$ at Demsa and Zaria, respectively (Fig. 2).

2.5. Soil characterisation at study sites

For model calibration and evaluation, soil samples were collected from the experimental sites and characterized according to the procedure of IITA (1989) (Table S1). The sand, silt and clay content of Dambatta soil were 80, 6 and 14 %, respectively. The surface horizon has a sandy loam texture and is moderately acidic (pH of 5.7). The soils have very low organic carbon content (3.6 g kg^{-1}), total N (TN) (0.26 g kg^{-1}) and available P (2.23 mg kg^{-1}). The sand, silt and clay contents of the soils at BUK-Kano are 68, 12 and 20 %, respectively. The soils were slightly acidic (pH of 6.5), with low TN (0.37 g kg^{-1}), available P (5.62 mg kg^{-1}) and low organic carbon content (4.4 g kg^{-1}). The soil at Zaria is loamy with sand, silt and clay contents of 38, 42 and 20 %, respectively. It is moderately acidic (pH of 5.7) and has very low TN of 0.8 g kg^{-1} , available P of 1.9 mg kg^{-1} and low organic carbon content (4.6 g kg^{-1}). The soil at the Abuja site is clayey with sand, silt, clay contents of 35 %, 16 % and 49 %, respectively, with pH of 5.9. The soil has low organic carbon (5.8 g kg^{-1}), TN content (0.31 g kg^{-1}), and available P of 6.2 mg kg^{-1} .

The soils at the model application sites were sampled and characterised using the above-mentioned procedures. For each soil layer, the model utilized the soil data tool *SBuild* in DSSAT to estimate parameters such as bulk density, drained upper limit (DUL), saturated upper limit (SAT), lower limit of plant available soil water (LL), saturated hydraulic conductivity (KSAT), and root growth factor. The soils at Demsa are sandy clay loam with 65 % sand, 15 % silt, and 20 % clay. The pH of the soil is 8.3 with TN, P, and OC contents of 0.6 g kg^{-1} , 3.8 mg kg^{-1} , and 6.6 g kg^{-1} , respectively. The soil at Puba Vidau is characterized as clay, with 18 % sand, 19 % silt and 63 % clay content. The pH is 8.3 with TN, P, and OC contents of 0.2 g kg^{-1} , 0.9 mg kg^{-1} , and 4.0 g kg^{-1} respectively (Table S2). The soils for BUK and Zaria are the same as the soils used for model calibration and evaluation sites.

2.6. Description of the CROPGRO cowpea-model

The CROPGRO-cowpea model was developed to simulate the growth and yield of cowpea crop. The CSM-CROPGRO-Cowpea model was adapted in 1999 by K. J. Boote and is based on the CROPGRO-Soybean model (Boote et al., 1998). This model uses the codes and structure of CROPGRO v. 3.5, as described by Tsuji et al. (1994) and Boote et al. (1998), but the input parameters that define cultivar and ecotype files were changed to characterize the cowpea crop. The model shares the same source code as the other CROPGRO legume models (Boote et al., 1998; Hoogenboom et al., 2019). This includes hedge-row light interception model (Boote and Pickering, 1994) combined with a leaf-scale photosynthesis model based on the Farquhar approach for simulating response to CO₂. Differences from soybean include: 1) more rapid early leaf area expansion, 2) shorter crop cycle, 3) short individual pod-filling duration that can limit yield, and 4) short rapid flushes of pod addition such that pods may mature even while new flushes of pods are being added. The model was evaluated for production of cowpea as a dual-purpose crop in Nigeria in a tripartite collaboration that involved the International Livestock Research Institute (ILRI), the International

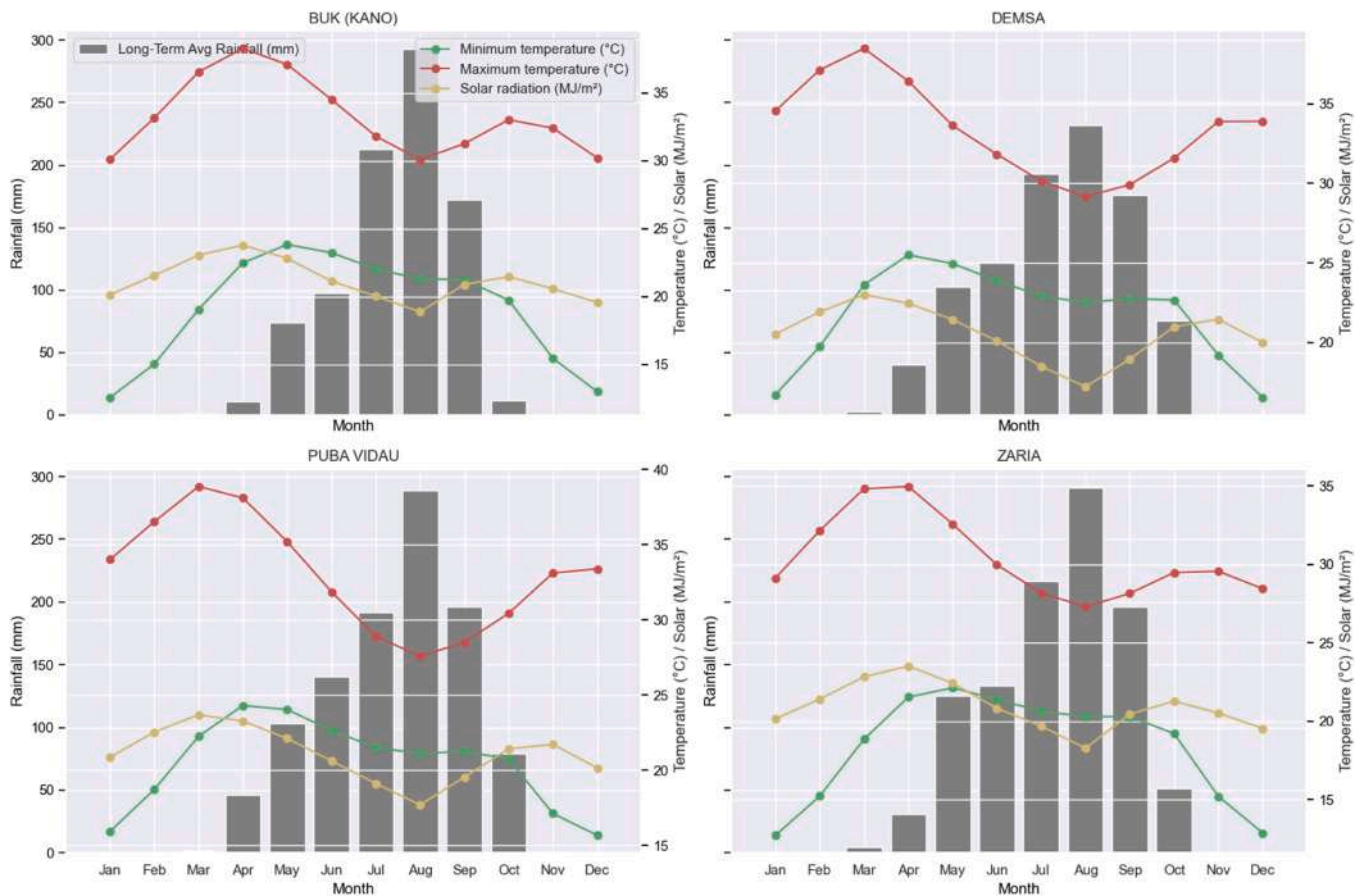


Fig. 2. Thirty-six years (1987–2022) monthly average precipitation, minimum and maximum temperatures, solar radiation across the four sites.

Institute of Tropical Agriculture (IITA), and the University of Georgia (Hoogenboom et al., 1999). The CROPGRO model requires genetic coefficients, which describe the durations of phases of the crop life cycle for vegetative growth traits and unique reproductive traits of a specific cultivar (Boote et al., 1998). These coefficients enable the CROPGRO growth model to predict variations in development, growth, and yield among cultivars under the same environmental conditions, as well as variations in the behaviour of a single cultivar across different environments (Tupe et al., 2017). The model requires 15 cultivar coefficients that describe the sensitivity to daylength (CSDL and PPSEN), phenology (EM-FL, FL-SH, FL-SD, SD-PM, FL-LF, SFDUR and PODUR) and growth trait (LFMAX, SLAVR, SIZLF, XFRT, WTPSD and SDPDV) for each cultivar. The definition and description of these coefficients are provided in Table 3.

2.7. CROPGRO – Cowpea model calibration and evaluation

The genetic coefficients for cowpea varieties were estimated through multiple simulations of the DSSAT CROPGRO-Cowpea model using the Genotype Coefficient Calculator (GENCALC). The cultivar coefficients for each variety were determined through an iterative process, comparing simulated and observed data. Calibration of the CROPGRO-cowpea model was conducted by establishing cultivar coefficients for each variety using the experimental data. Except for SAMPEA 9, which is already embedded in the model as IT90K-277-2, coefficients for other parameters were unavailable for the varieties utilized in these experiments. Consequently, existing cultivar coefficients for the cultivar IT86D-719 served as a template for the other two varieties (SAMPEA 14 and FUAMPEA 1) at the onset of calibration due to their representation of tropical cowpea varieties.

The model accuracy in predicting planting date for cowpea growth

and yield was evaluated using the six independent field experiments described earlier. Similarly, the sowing dates in the model were set exactly to reflect the experimental sowing dates. For the evaluation, the population density was set at 13.3 plants m^{-2} with P and K applied at the rate of 40 kg ha^{-1} each of P_2O_5 and K_2O in the form of Triple Superphosphate and Muriate of potash, respectively. Data used for the evaluation includes days to flowering, days to physiological maturity, total dry matter and grain yield at harvest.

2.8. Model evaluation statistics

The model's performance in simulating the crop growth and development was assessed using root mean square error (RMSE) [Eq. 1], normalized root mean square error (nRMSE) [Eq. 2] based on previous model evaluation studies (Yang and Huffman, 2004; Liu et al., 2011), and d statistic [Eq. 3] (Willmott, 1985).

$$RMSE = \sqrt{\frac{\sum (O_i - P_i)^2}{n}} \quad (1)$$

Where: P_i = predicted value, O_i = observed value and n = number of observations.

$$nRMSE = \frac{RMSE \times 100}{\bar{O}} \quad (2)$$

Where $\bar{O}$ 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 the nRMSE is > 20 % and < 30 %, and poor if the nRMSE is > 30 % (Jamieson et al., 1991). The d -index statistic is recommended for making cross-comparisons when the d value is both relative and has bounded measures

Table 3

Genetic coefficients of cowpea cultivars used in the study.

Coefficient	Definition	Unit	SAMPEA 9	SAMPEA 14	FUAMPEA 1
CSDL	Critical Short-day length below which reproductive development progresses with no day-length effect (for short-day plants)	Hour	12.8	12.8	12.7
PPSEN	The slope of the relative response of development to photoperiod with time (positive for short-day plants)	1/ hour	0.294	0.294	0.181
EM-FL	The time between plant emergence and flower appearance (R1)	PTD	34.14	30.5	30.68
FL-SH	The time between the first flower and the first pod (R3)	PTD	3	2.5	3.59
FL-SD	The time between the first flower and the first seed (R5)	PTD	6	6	7.15
SD-PM	Time between first seed (R5) and physiological maturity (R7)	PTD	20	18	15.36
FL-LF	Time between first flower (R1) and of leaf expansion	PTD	18	5	10
LFMAX	Max leaf photosynthesis rate 30°C, 350 ppm CO ₂ , high light intensity	mg CO ₂ / m ² /s	1	1	0.982
SLAVR	Specific leaf area of cultivar under standard growth conditions	cm ² / g	325	275	223.3
SIZLF	Maximum size of full leaf (three leaflets)	cm ²	150	150	150
XFRT	Maximum fraction of daily growth partitioned to seed + shell		0.9	1	0.586
WTPSD	Maximum weight per seed	G	0.6	0.24	0.093
SFDUR	Seed filling duration for pod cohort at standard growth conditions	PTD	8	9	9.1
SDPDV	Average seed per pod under standard growing conditions	no./ pod	3.5	6.5	3.5
PODUR	Time required for cultivar to reach final pod load under optimal conditions	PTD	16	14	9

PTD = Photo-thermal days, no./pod=number of seeds per pod

(Willmott, 1985).

$$d = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (|P_i| + |O_i|)^2} \quad (3)$$

Where: P_i = predicted value at location i , O_i = observed value at location i and n = number of observations.

The Microsoft excel software was used to graph and compare simulated model outputs with observed data (Liu et al., 2013). Easy Grapher program in DSSAT v4.7 was used to calculate model performance statistics (Yang and Huffman, 2004).

2.9. Long-term simulation of cowpea varietal performance under varying sowing windows and planting densities

The DSSAT 4.7.5 (Hoogenboom et al., 2019) seasonal analysis tool was used to evaluate the yield performance of three cowpea varieties over 36 years (1987–2022) across four sites, considering different plant densities and sowing windows in two agroecological zones of the Nigerian savannas. The simulation sites are in Zaria and Demsa in the NGS AEZ, and Puba Vidau and BUK (Kano) in the SS AEZ. For the simulation of cowpea response to changes in plant density, three plant densities of 13.3, 26.6, and 40 plants m⁻² were used with the planting date set to July 1–7 for all 36 years of simulation. For the simulation of cowpea response to sowing dates, six sowing windows were used. These were SW1: July 1–7, SW2: July 8–14, SW3: July 15–21, SW4: July 22–28, SW5: July 29–August 04 and SW6: August 05–11. For the seasonal analysis, optimal recommended phosphorus fertilizer rates of 40 kg ha⁻¹ each of P₂O₅ and K₂O were applied. In the model, the water balance module was enabled to account for soil moisture availability and water stress effects on the crop growth and yield. The model was set to harvest when the crop reaches maturity.

2.10. Data analysis

For the scenario analysis, to determine whether sowing window, planting density, and variety influence grain yield outcomes, a linear mixed effects (LMEs) models was fitted with sowing window, planting density and variety and their two-way interactions as ‘fixed term’ and year as ‘random effect’. The LMEs models were fitted using ‘nlme’ package in R (Pinheiro et al., 2023). Significant means were pairwise-compared using Tukey HSD test based on estimated marginal means using the ‘emmeans’ package in R (Lenth, 2024). High -stable index (HSI) was used as metric to determine the optimal sowing window × planting density combination that maintains stable cowpea grain yield over the simulation period. The HSI was calculated based on Zhao and Yang (2019) as follows:

$$HSI = \frac{\bar{x}_i - \sigma}{\bar{x}} \quad (4)$$

Where $\bar{x}_i$ is the mean grain yield for each sowing window × density combination, σ = is the standard deviation and $\bar{x}$ is the grand mean for all combinations. Based on this, HSI thresholds of < 0.23, 0.23–0.63, and > 0.63, were classified as low, intermediate, and high stability, respectively.

3. Results

3.1. Model calibration and evaluation

Cultivar-specific parameters for the three varieties are presented in Table 3. The critical short-day length (CSDL) range was similar for all the varieties and was 12.7 h (FUAMPEA 1) and 12.8 h for both the SAMPEA varieties. The photoperiod sensitivity (PPSEN) coefficient also shows a similar value for the SAMPEA varieties (0.2940/h). The EM-FL coefficient ranged from 30.50 (for SAMPEA 14) to 34.14 (SAMPEA 9).

The coefficient explaining the first flower to first pod appearance (FL-SH) was highest for FUAMPEA 1 (3.59 PTD), while the duration from first flower to first seed (FL-SD) varied from 6.0 to 7.15 PTD. The time from first seed to physiological maturity (SD-PM) ranged from 15.36 to 20.00 PTD. The time between first flower and end of leaf expansion (FL-

LF) was the longest for SAMPEA 9, with a value of 18.00 compared to other varieties. The maximum size of a full leaf (SIZLF) was consistent across all cultivars at 150.0 cm². The coefficient for seed filling duration (SFDUR) was also similar for all the varieties.

Results show that the model adequately captured the phenology,

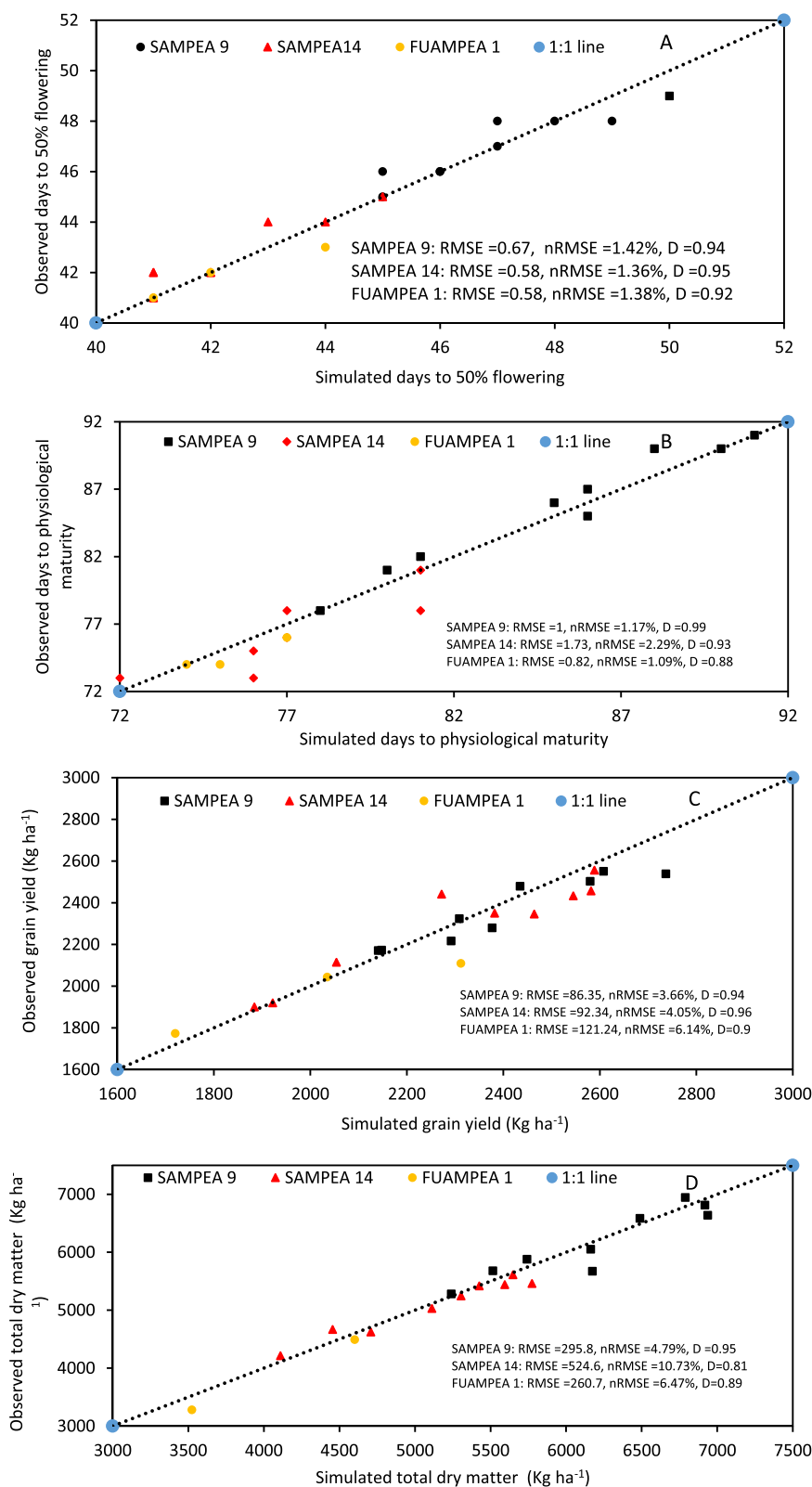


Fig. 3. Comparison of simulated and observed calibrated parameters: (A) Days to 50 % flowering (B) Days to physiological maturity, (C) final grain yield, and (D) final total dry matter of SAMPEA 9, SAMPEA 14 and FUAMPEA 1.

total dry matter, and grain yield of the cowpea varieties (Fig. 3A-D). The d-index values ranged from 0.92 to 0.95 for days to 50 % flowering, 0.88–0.99 for days to physiological maturity, 0.81–0.95 for total dry matter, and 0.90–0.96 for grain yield across all varieties. The RMSE values for days to 50 % flowering, ranged from 0.58 to 0.67 days, and the nRMSE values ranged from 1.36 % to 1.42 % (Fig. 3A). For days to physiological maturity, the RMSE values ranged from 0.82 to 1.73 days, with nRMSE values ranging from 1.09 % to 2.29 % (Fig. 3B). For grain

yield, the RMSE values ranged from 86.35 to 121.24 kg ha⁻¹, and the nRMSE values ranged from 3.66 % to 6.14 % (Fig. 3C). The RMSE values of total dry matter ranged from 260.7 to 295 kg ha⁻¹, while the nRMSE values ranged from 4.79 % to 10.73 % (Fig. 3D). These statistical indices indicate good agreement between observed and simulated values for all measured parameters across the three cowpea varieties.

In evaluating the model with independent data sets, the simulated values for SAMPEA 9, SAMPEA 14, and FUAMPEA 1 show good

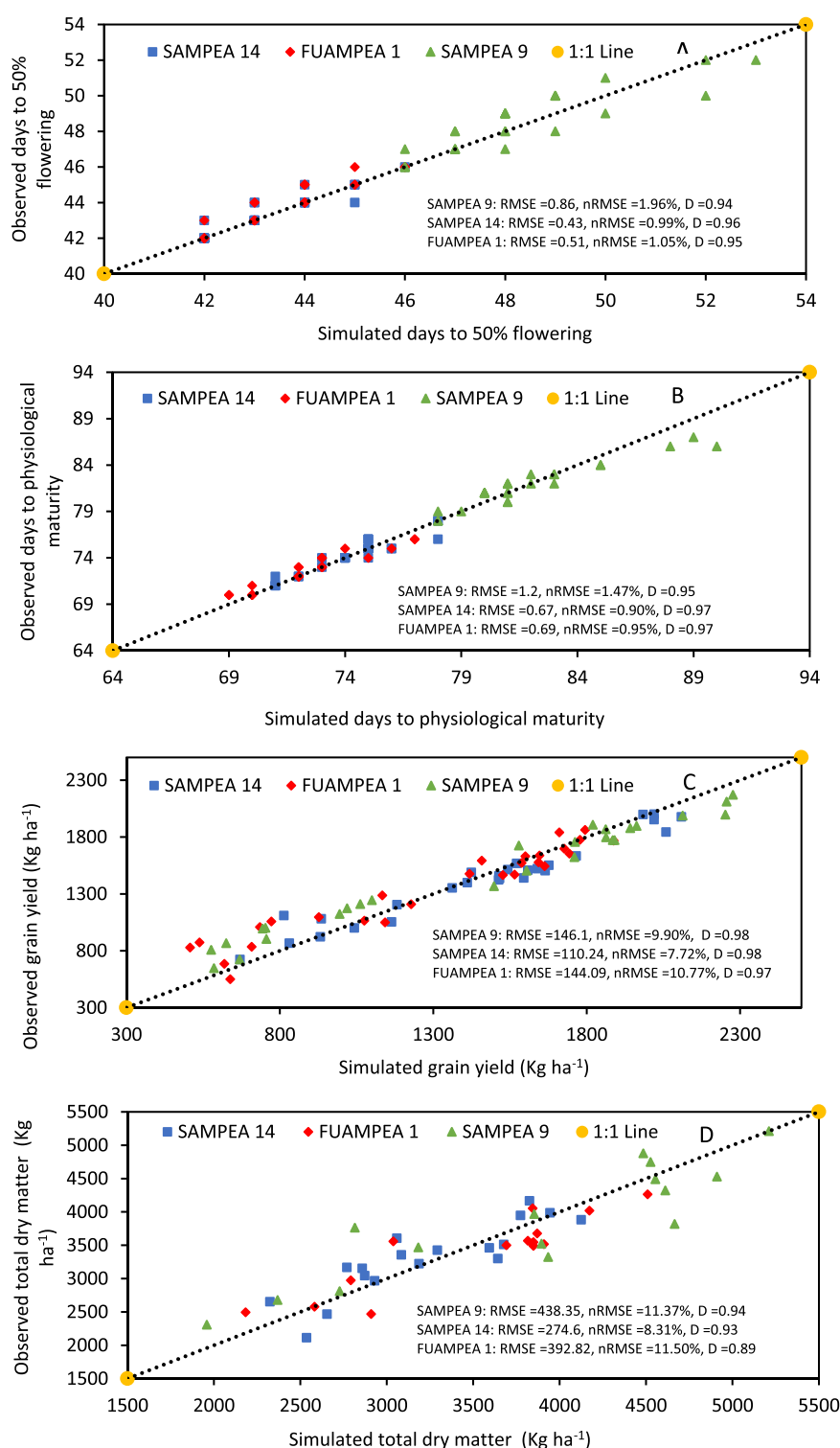


Fig. 4. Results of model evaluation based on sowing dates using (A) Days to 50 % flowering (B) Days to physiological maturity (C) final grain yield and (D) final total dry matter for SAMPEA 9, SAMPEA 14 and FUAMPEA 1 at two model evaluation sites: Zaria and Abuja.

agreement with their corresponding observed values (Fig. 4A–D). Specifically, for days to 50 % flowering, the d-index values ranged from 0.94 to 0.96, with RMSE and nRMSE values ranging from 0.43 to 0.86 days and 0.99–1.96 %, respectively (Fig. 4A). For physiological maturity, the d-index values ranged from 0.95 to 0.97, with RMSE and nRMSE values ranging from 0.67 to 1.2 days and 0.90–1.47 %, respectively (Fig. 4B). The model's performance in reproducing total dry matter and grain yield was also excellent. The d-index values for grain yield ranged from 0.97 to 0.98, with RMSE and nRMSE values ranging from 110 to 146.0 kg ha⁻¹ and 7.72–10.8 %, respectively (Fig. 4C). For total dry matter, the d-index values ranged from 0.89 to 0.94, with RMSE and nRMSE values ranging from 274.6 to 438.4 kg ha⁻¹ and 8.31–11.5 %, respectively (Fig. 4D). These results collectively indicate the model's robustness and accuracy in predicting various aspects of phenology, total dry matter, and final grain yield, and it can therefore, be used to simulate the response of the cowpea varieties to crop management practices.

3.2. Seasonal analysis

3.2.1. Effects of variety, sowing window and plant density on grain yield

Overall, the mean long-term grain yield was in the order Zaria (1119 kg ha⁻¹) > BUK (901 kg ha⁻¹) > Demsa (790 kg ha⁻¹) > Puba Vidau (575 kg ha⁻¹) (Fig. 5). The main effects of variety, planting density and sowing window were significant in all the locations (Table 4). Averaged across locations, SAMPEA 9 had the highest grain yield (934 kg ha⁻¹), while FUAMPEA 1 had the least (780 kg ha⁻¹). There was a linear decrease in grain yield with delayed planting, where highest average yield was simulated for SW1 (1086 kg ha⁻¹), while the least average yield was simulated for SW6 (652 kg ha⁻¹). A similar trend was simulated with density, where yield increases significantly with increasing planting density (Fig. 5). However, SAMPEA 9 was not sensitive to increased planting density in all the locations.

At Demsa in the NGS, average grain yield was lowest for SAMPEA 14 (702 kg ha⁻¹), followed by FUAMPEA 1 (745 kg ha⁻¹) and highest for SAMPEA 9 (922 kg ha⁻¹). The mean grain yield of FUAMPEA 1 was highest (1177 kg ha⁻¹) when sown at high density (40 plants m⁻²) between July 1–14 (SW1 and SW2). Lowest grain yields (435 – 470 kg ha⁻¹) were simulated with, delayed sowing in late July through August (SW3–SW6) at 13.3 plants m⁻² followed by 26.6 plants m⁻² (581 – 634 kg ha⁻¹), and 40 plants m⁻² (658 – 717 kg ha⁻¹). A similar trend was simulated for SAMPEA 14. There was an increase in grain yield with increasing plant density but delayed sowing to late July or August resulted in significantly lower grain yield than planting on July 1 – 14. A different trend was simulated for SAMPEA 9 where sowing window was more important than density. Lowest grain yield was simulated with sowing in SW6, but this was statistically similar to with other sowing windows. However, differences among sowing windows were not significant ($p > 0.05$).

At Zaria in the NGS, the grain yield was consistently higher at higher density than low density irrespective of sowing window and variety choice. There was no significant interaction between sowing window and density in the case of SAMPEA 9 and the yield averaged 1200 kg ha⁻¹. For SAMPEA 14, planting early on July 1 – 7 (SW1) or delaying planting until July 22 – 29 (SW4) produced the highest grain yield (> 1200 kg ha⁻¹) at 40 plants m⁻². Low density (13.3 plants m⁻²) consistently had the lowest grain yield irrespective of the sowing window. In the case of FUAMPEA 1, planting on July 22 – 29 (SW4) at 40 plants m⁻² produced the highest grain yield.

Across all the three varieties at BUK in the SS, planting early on July 1 – 7 (SW1) at moderate (26.6 plants m⁻²) and high (40 plants m⁻²) plant densities resulted in yield > 1000 kg ha⁻¹ (Fig. 5). Delayed planting until late July (SW3 and SW4) or August (SW5 and SW6) consistently resulted in low yield (< 800 kg ha⁻¹) irrespective of variety and planting density. Compared to SAMPEA 14 and FUAMPEA 1, SAMPEA 9 produced the least grain yield (< 400 kg ha⁻¹) at the latest sowing window

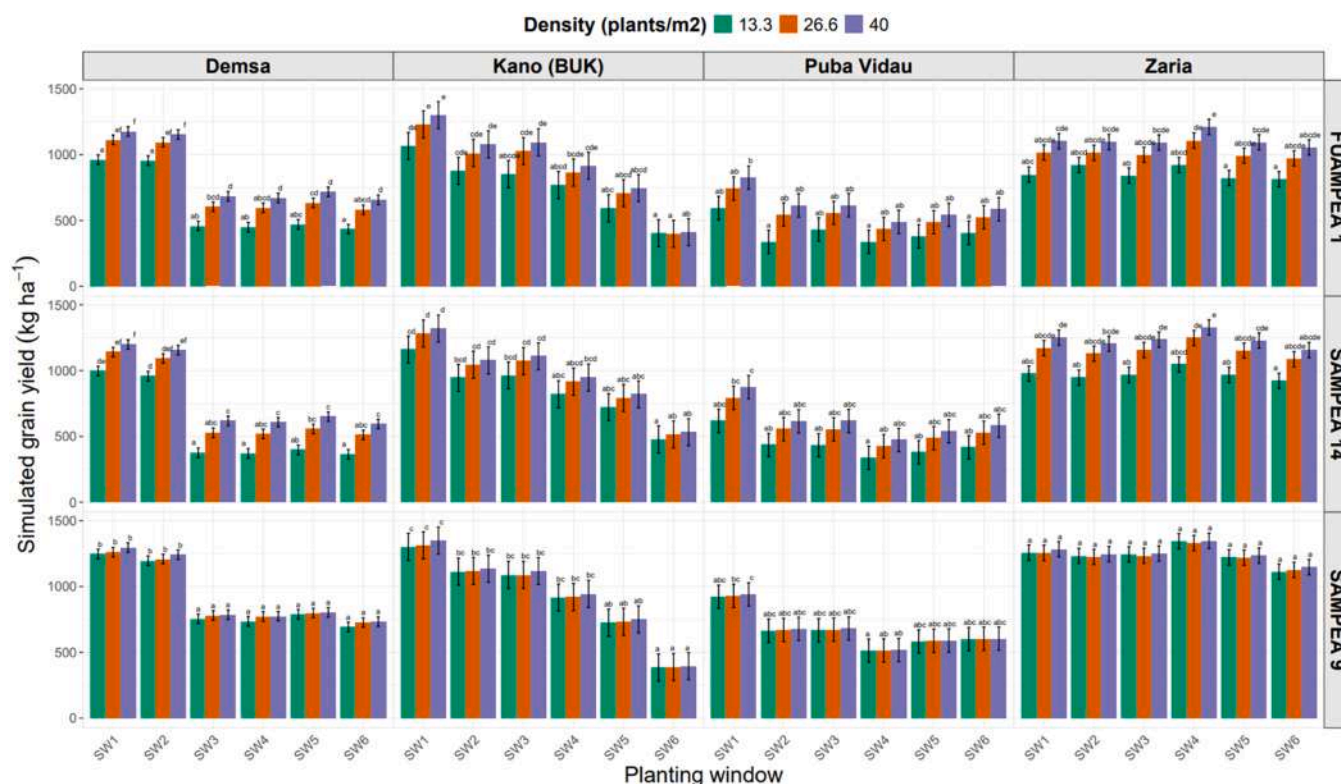


Fig. 5. Long-term mean average grain yield response to sowing window and density across the four sites for each variety. Error bars are variation (standard errors) due to management variation within a site and variety. SW1: July 1–7, SW2: July 8–14, SW3: July 15–21, SW4: July 22–29, SW5: July 29–August 04, SW6: August 05–11.

Table 4

Summary of linear mixed effects model (LMEs) showing the main and interaction effects of density, sowing window, and variety on simulated grain yield for the period 1987 – 2022, inclusive across the four sites. Values in bold face are significant at $p < 0.05$.

Source of variation	Demsa		Zaria		Kano (BUK)		Puba Vidau	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
(Intercept)	3723.036	< .0001	373.878	< .0001	1795.149	< .0001	361.378	< .0001
Density	202.764	< .0001	11.368	0.001	101.508	< .0001	21.424	< .0001
Sowing window	563.673	< .0001	88.351	< .0001	9.438	< .0001	19.142	< .0001
Variety	212.040	< .0001	3.803	0.023	98.852	< .0001	15.114	< .0001
Density × Sowing window	0.102	0.992	0.345	0.886	0.125	0.987	0.167	0.975
Density × Variety	30.532	< .0001	1.744	0.175	20.979	< .0001	4.598	0.010
Sowing window × Variety	2.344	0.010	0.612	0.805	0.461	0.916	0.231	0.993
Density × Sowing window × Variety	0.144	0.999	0.093	1.000	0.119	1.000	0.059	1.000

(SW6). For the lowest yielding site (Puba Vidau) in the SS, sowing early in July (SW1) at moderate (26.6 plants m^{-2}) and high (40 plants m^{-2}) plant density consistently resulted in highest yield irrespective of variety. Lowest yielding scenario was plant density of 13.3 plants m^{-2} and July 22 – 29 (SW4) sowing window (Fig. 5).

3.3. Optimal sowing window and density combination

We use the HSI as a metric to identify the optimal sowing window × planting density combination that maximizes grain yield of variety across locations (Fig. 6). In the low-yielding site (Demsa), the HSI varies from 0.25 – 1.42 with the optimal combination being SAMPEA 9 sown in July 1 – 7 (SW1) at either 40 plants m^{-2} (HSI = 1.42; average yield = 1296 ± 95 kg ha^{-1}), 26.6 plants m^{-2} (HSI = 1.38; average yield = 1261 ± 92 kg ha^{-1}), or 13.3 40 plants m^{-2} (HSI = 1.36; average yield = 1248 ± 89 kg ha^{-1}). The most sub-optimal combination was cowpea sown on SW6 at 13.3 plants m^{-2} (HSI = 0.25; average yield = 364 ± 152 kg ha^{-1}). At BUK (Kano), the HSI had narrow range with optimal combination being SAMPEA 9 sown on July 1 – 7 (SW1) at 40 plants m^{-2} (HSI = 1.01; average yield = 1348 ± 492 kg ha^{-1}) while the lowest yielding combination was FUAMPEA 1 sown on SW6 at 40 plants m^{-2} (HSI = 0.10; average yield = 412 ± 500 kg ha^{-1}). In the lowest yielding site (Puba Vidau), optimal sowing window × density combination was

for SAMPEA 9 sown early in July (SW1) at 40 plants m^{-2} (HSI = 0.50; average yield = 940 ± 514 kg ha^{-1}), 26.6 plants m^{-2} (HSI = 0.49; average yield = 929 ± 508 kg ha^{-1}), or 13.3 40 plants m^{-2} (HSI = 0.49; average yield = 922 ± 506 kg ha^{-1}). The most sub-optimal combination was SAMPEA 9 sown on SW4 at 40 plants m^{-2} (HSI = 0.12; average yield = 517 ± 622 kg ha^{-1}). In the highest-yielding site (Zaria), all the varieties sown either in SW4 or SW1 produced significantly high HSI values (> 1.0 ; average yield > 1200 kg ha^{-1}). However, FUAMPEA 1, when sown late (SW5 and SW6) produced the lowest yield (< 900 kg ha^{-1}) and HSI (< 0.6), thus was the suboptimal management option (Fig. 6).

4. Discussions

4.1. Model calibration and evaluation

The CROPGRO model has previously been used to simulate the performance of many legume crops (Bebeley et al., 2022, Kamara et al., 2023), but only very few studies have calibrated and evaluated the CROPGRO–cowpea model to simulate cowpea performance. Our model calibration results show that the CROPGRO–cowpea model accurately reproduced the observed values for days to 50 % flowering, days to maturity and grain yield. The *d-index* values ranged from 0.92–0.95 for flowering, 0.88–0.99 for days to maturity and 0.9–0.96 for grain yield.

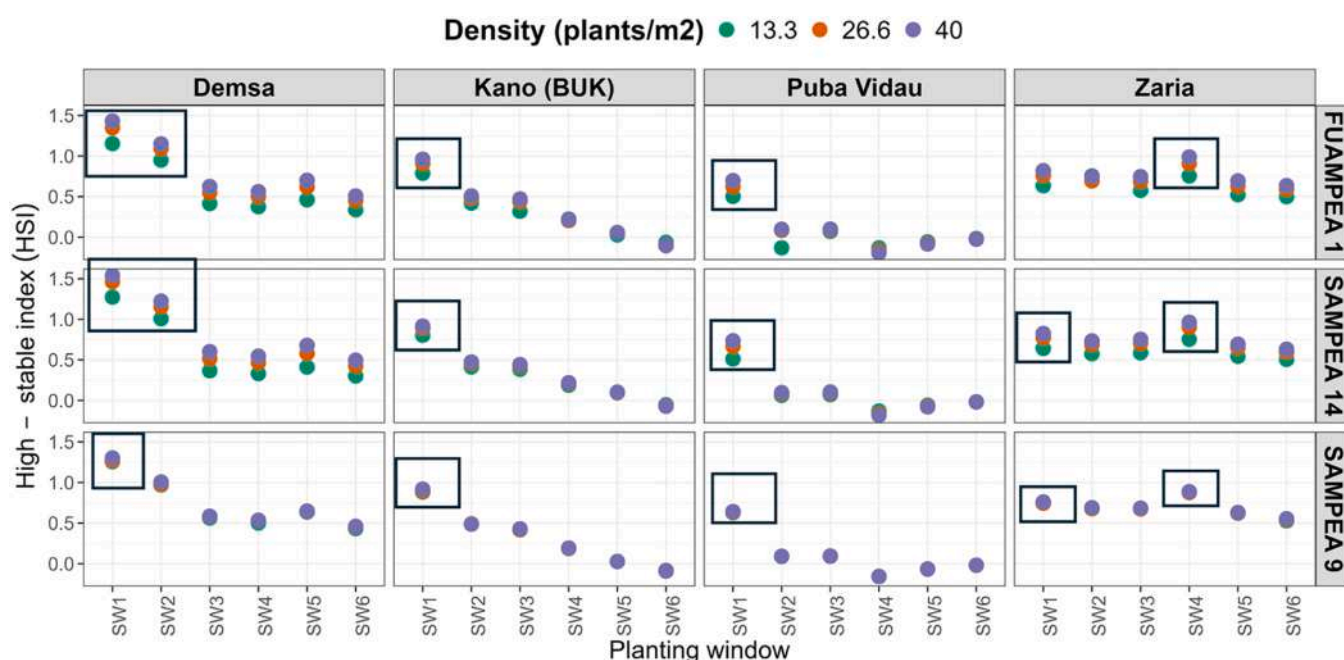


Fig. 6. High –stable index (HSI) showing the sowing window and planting density interaction for the three cowpea varieties across the four different sites. Optimal sowing window × planting density combination (achieving > 75 % of the high are shown in black rectangle for each site and variety. HSI thresholds of < 0.23 , 0.23–0.63, and > 0.63 , were classified as low, intermediate, and high stability, respectively. SW1: July 1–7, SW2: July 8–14, SW3: July 15–21, SW4: July 22–29, SW5: July 29–August 04, SW6: August 05–11.

The nRMSE values were $< 12\%$ for all parameters for the 3 varieties. The results of the model evaluation also show that the model was able to reasonably simulate the phenology and grain yield of cowpea for different sowing windows with low RMSE and high d-index values (Fig. 4). The results are consistent with those found in the few available simulation studies for cowpea by Filho et al. (2013) in Bahia, Brazil, Bastos et al. (2002) in Piauí State, Brazil, and by Lomeling et al. (2014); Lomeling and Huria, (2019); (2020) in Sudan. Our results confirm the ability of the CROPGRO–cowpea model to accurately predict the growth and yield of rainfed cowpea in the Nigeria savannas. The results suggest that the DSSAT–cowpea model can be used to simulate the performance of cowpea in response to crop management practices in the Nigeria savannas.

4.2. Long-term impacts of sowing window and density on yield

The long-term simulation results show that cowpea performance is strongly influenced by location, variety, and crop management practices such as planting density and sowing window. The yields recorded at Zaria were higher than those of other locations because of good rainfall distribution and more fertile soils at that site. Bebeley et al. (2022) reported higher yields of soybean at Zaria than in other locations because of good growing conditions. In two of the locations (Zaria in NGS and BUK–Kano in SS), the yields were $> 1000\text{ kg ha}^{-1}$, particularly when planted early in July 1–7 SW and at moderate to high density. Compared to Demsa in the NGS, the higher yield in Kano may be related to higher solar radiation ($r > 0.77$, $p < 0.05$), which provides energy to plants for photosynthesis (Guo et al., 2022). The weather data used in the long-term simulations has indicated a very low solar radiation (Fig. 2; Fig. S1) between July and September in Demsa, and that might have coincided with the critical reproductive stages of the cowpea. Low solar radiation during critical reproductive stages can limit photosynthetic activity and reduce assimilate availability for grain filling (Taiz and Zeiger, 2010). Previous studies have simulated higher grain yield of maize (Tofa et al., 2020) and soybean (Bebeley et al., 2022) in the NGS than in the SS. Also, the weather results show that minimum and maximum temperatures were significantly lower in Demsa than in Kano and Zaria. Lower temperatures can also limit cowpea production, especially if they fall below the critical thresholds for germination, flowering, or pod filling. In the same study, Kamara et al. (2023) simulated higher grain yield of rainfed soybean for most of the locations in the drier SS than for the NGS in northeast Nigeria and concluded that rainfall distribution is needed to explain the lower yield in areas that have sufficient total amount of rainfall. Furthermore, a very high variation in soil properties (Peter-Jerome et al., 2022; Aliyu et al., 2020), and its effect on crop yield (Aliyu et al., 2022) have been reported across the Nigeria savannas. Similarly, Kamara et al. (2023), attributed differences in soil type and fertility among 24 sites and between the agroecological zones to be the cause of yield variation of soybean in northeast Nigeria. The yield difference among locations could, therefore, also be attributed to the difference in the soil texture. Cowpea normally does well on well-drained sandy-loam soils. The soils at Demsa are very sandy (65 %), which can affect nutrient and water retention. On the other hand, the soils at Zaria have lower sand content (38 %) and high silt content (42 %) which might help in nutrient and water retention. Furthermore, the soils at Demsa have lower available P (3.8 mg kg^{-1}), compared to the soils at BUK (Kano) (5.6 mg kg^{-1}). P effect was however, not accounted for in the model.

While many mechanistic models for P uptake have been developed in the past (Greenwood et al., 2001a, 2001b) with emphasis on the soil aspects that affect P availability, the linkage to whole crop models has been limited (Naab et al., 2015). A generic soil-plant P module is available in DSSAT and has been tested on crops such as maize (Dzotsi et al., 2010), peanut (Halder et al., 2017), sorghum (Adam et al., 2018), and soybean (Bebeley et al., 2022) but not on cowpea. Bebeley et al. (2022) found that the CROPGRO–Soybean model performed more

accurately in predicting all measured parameters when phosphorus was applied, compared to no phosphorus application. This agrees with the findings of Naab et al. (2015), who observed high accuracy of prediction with high P-fertilizer rate and lower prediction accuracy under low or no P-fertilizer application when simulating for groundnut growth using CROPGRO–Peanut. Nevertheless, the limited ability of the DSSAT model to simulate P response for cowpea is still a major limitation for the use of DSSAT model (Dzotsi et al., 2010).

There were significant differences among the three varieties for grain yield with a notable interaction between variety and plant density. Our simulations indicate that SAMPEA 9 exhibits a reduced response to increased plant density compared to the early-maturing varieties FUAMPEA 1 and SAMPEA 14. Our result is consistent with the findings of Solomon (2025) who in a multi-year and locational trial in northern Nigeria, reported that SAMPEA 9 did not respond to increases in plant density beyond $13,333\text{ plants ha}^{-1}$. This is likely due to several factors. The model-calibrated genetic coefficients suggest that SAMPEA 9 has a larger seed size (0.6 g) than the other cultivars (0.24 g and 0.093 g), resulting in a higher initial leaf area index (LAI) that promotes rapid canopy closure and diminishes the yield benefits of increased plant density. The model is designed to give larger initial LAI in response to seed size. According to Jones et al. (2003), seed size is used as a key parameter that influences the initial leaf area, thereby affecting early canopy development in the model. In addition, the higher SLAVR, late flowering time and extended period for leaf area expansion for SAMPEA 9 (Table 3) may enhance its LAI development, thereby reducing its sensitivity to plant density (Ismail and Hall, 2000). Its thinner leaves may also affect light interception and photosynthetic efficiency (Bruns, 2011; Corassa et al., 2018). In contrast, the smaller seed size of FUAMPEA 1 likely contributes to a lower initial LAI, making it more responsive to higher plant densities (Carciochi et al., 2019).

In a field experiment in the Nigeria savannas, Kamara et al. (2016) found no significant response of cowpea varieties to increases in plant densities beyond 26 plants m^{-2} . Our simulations show that the current density of $13.3\text{ plants m}^{-2}$ is not optimal for early-maturing varieties. Adjusting planting density is an important tool to optimize crop growth, canopy closure, biomass, and grain yield (Liu et al., 2008); seasonal analysis revealed higher grain yield at 40 plants m^{-2} for the early maturing varieties, with a considerable increase from 13.3 to 26 plants m^{-2} . Therefore, taking into account the cost of seed for farmers, a plant density of 26 plants m^{-2} is recommended in the Nigeria savannas. However, the ultimate yield response depends on cultivar adaptation to the specific environment (Corassa et al., 2018; Carciochi et al., 2019).

The results show that the optimal sowing windows were dependent on the location and cowpea variety probably due to differences in soil types, rainfall amounts, and patterns across sites and AEZs (Akinseye et al., 2020). In the Guinea savannas, sowing could be delayed to July 14 for SAMPEA 14 and FUAMPEA 1 and to July 7 for SAMPEA 9 in one of the locations (Demsa) and to July 29 in Zaria for all the varieties without any significant reduction in yield. This suggests that the Guinea savannas have a wider sowing window of July 1–29 beyond which there will be a significant reduction in yield. Other authors (Tofa et al., 2020; Bebeley et al., 2022) reported that Zaria has a long growing season and favourable soil conditions for grain crop production. For example, Bebeley et al. (2022) reported that soybean can be sown between June 1 and July 12 in this location. In the Sudan savanna AEZ, the length of sowing period is about 15 days, irrespective of location and variety. To obtain optimal yield, sowing should be done between July 1 and 15, beyond which there will be significant reduction in yield. The rains usually stop at the end of October in the Guinea savanna and at the end of September in the Sudan savanna AEZ. Late planting at the end of July or sometime in August can cause in-season water deficit for the cowpea crops. Also, for the SS, planting should be done at the beginning of July to mid-July to avoid end of seasonal water deficit at the end of September.

4.3. Optimal sowing window $\times$ planting density combination that maximizes grain yield of variety across locations

In rainfed cropping systems, wide yield gaps exist and identifying optimal combinations of genotype, agronomic management (e.g., sowing windows and planting density) and matching these combinations to the prevailing growing environments could be a key to closing these yield gaps. Here, HSI was used as a metric to summarize the patterns and relationships of cowpea varietal selection and management interactions across different environments. Our simulations show that the most stable and widely adaptable cowpea variety in all locations is SAMPEA 9 irrespective of sowing window and planting density. The variety SAMPEA 9 (previously IT90K-277-2) is one of the oldest and most widely grown cowpea varieties in the savanna agroecological zones (Kouakou et al., 2022). The variety is a semi-erect medium maturing with moderate photoperiod sensitivity (Danlami et al., 2015).

For both short and long-term adaptation strategies, it is important to consider cowpea yield stability when evaluating optimal crop management decisions (Popoola et al., 2024). Here, optimal management combinations correspond to sowing window and density combinations that consistently maintained high HSI in each location and these were predicted to change considerably with increasing precipitation and length of growing seasons. In the high rainfall environment (Zaria), planting early in SW1 and in SW4 at 40 plants m^{-2} produced the highest yield, irrespective of the cowpea variety. This is expected as sowing in SW2 and SW3 means heavy rainfall and cloud cover and reduced radiation during this period which negatively affect cowpea growth and yield. Cowpeas are commonly grown in the tropics in August under reduced solar radiation due to dense cloud cover and shading from plantation or tall intercrops. Planting in August when solar radiation is lowest may affect cowpea growth and yield. In a study of the effects of various radiation regimes on the performance of several grain legumes in the field during the warm and cool seasons in Hawaii, USA, Eriksen and Whitney (1984) reported that shading during the cool season reduced yield of grain legumes by 34 %. Of three grain legumes (cowpea, bush bean and soybean), low solar radiation reduced cowpea yield the most. Sowing later in SW5 or SW6 would lead to the crop experiencing water stress due to the cessation of rainfall at the end of the season. Furthermore, because water availability did not constrain growth, competition due to the high density (40 plants m^{-2}) in this location did not result in low yield outcomes. A similar trend was predicted at BUK (Kano), but yield penalties due to late sowing were larger and more frequent, probably due to the very low rainfall in October at the end of the season (Fig. 2).

Interestingly, in Puba Vidau where rainfall amount and distribution follow the pattern of Zaria, yields were consistently low, and the optimal management combination was early sowing window (SW1) using SAMPEA 9 at 13.3 plants m^{-2} while sowing later at SW4 resulted in the lowest yield and HSI. The plausible reason for this could be the significantly lower solar radiation recorded in Puba Vidau compared to Zaria. (Fig. 2) which may negatively affect cowpea growth. At the AP horizon, the soils in Puba Vidau are clay-rich (63 % clay fraction) and exhibit higher drained upper limit (DUL = 0.469) and water content at saturation (SAT = 0.474) values compared to the other locations. In DSSAT, high clay content often results in slower root water uptake. Moreover, when the soil moisture approaches saturation (SAT) under heavy rainfall, the model activates an “excess water stress” response which can lead to root damage and reduced photosynthesis (Ritchie, 1998; Manghwar et al., 2024). Cowpea is highly sensitive to waterlogging, especially during reproductive stage (Timsina et al., 1994; Olorunwa et al., 2022; 2023).

SAMPEA 9 sown at 13.3 plants m^{-2} in SW1 resulted in the highest HSI and mean yield in Demsa, making it the best management option. Consistent with other sites, precipitation, minimum and maximum temperatures and solar radiation are the main causes of the differences in yield outcomes and thus stability in Demsa compared to Zaria. The

soils at Demsa are sandy (65 % sand) compared to Zaria (38 % sand). Thus water retention is lower at Demsa which may cause simulated water stress during grain-filling period when cowpea is planted late in the season. Moreover solar radiation and minimum and maximum temperatures during the growing season were lower at Demsa than at Zaria which may have affected cowpea growth (Supplemental Fig. S1 and S2.). As SAMPEA 14 and FUAMPEA 1 are photo-insensitive, early sowing provides an opportunity for rapid phenological development, resulting in early flowering and less excessive vegetative growth (Danlami et al., 2015).

One of the limitation of this study is that the predictions are point-based, which do not account for the spatial heterogeneity of weather, soil, cultivars, and crop management (Guo et al., 2010). As spatial data become more accessible, relying solely on point-based simulations may limit their applicability for decision-making. Future research could integrate DSSAT simulation outputs with GIS tools to generate spatially continuous datasets, enhancing the accuracy and scalability of results. GIS-based mapping can facilitate the broader dissemination of agronomic technologies, reducing the time and costs associated with site-specific field experiments. In addition to design for site-specific simulations, the CROPGRO-cowpea is not able to simulate the response of cowpea varieties to application of P. The limited ability of the DSSAT model to simulate P response for cowpea is still a major limitation for the use of DSSAT model (Dzotsi et al., 2010). Further simulation studies are needed to determine whether P could play a role in the differential performance of cowpea among locations in the Nigeria savanna. Our simulation used already existing genetic information in the DSSAT model for SAMPEA 9 instead of using a real time data. This is a limitation in this study because the model appears to have over-estimated the seed weight of this variety. Information available on seed weight was generated under water and nutrient-limiting uncontrolled environments (Ezeaku et al., 2012). A further study to confirm the seed weight of SAMPEA 9 under optimal conditions (water and nutrient non-limiting, adequate insect control) in the Nigeria savannas is recommended.

5. Conclusion

The CROPGRO-Cowpea model was calibrated and evaluated to simulate the performance of three cowpea varieties with different maturity periods. Following the calibration and evaluation, the long-term water-limited yields of the three varieties were simulated across a range of growing environments to identify optimal sowing window and planting density. The long-term simulation scenarios show SAMPEA 9 was the most yield-stable variety with wide adaptation across the test environments and did not require planting density above the current industry recommendations of 13.3 plants m^{-2} . Seasonal analysis showed that early-maturing varieties (SAMPEA 14 and FUAMPEA 1) had higher grain yields at 40 plants m^{-2} , with a significant increase from 13.3 to 26 plants m^{-2} . Considering seed costs, a density of 26 plants m^{-2} is recommended for the Nigeria savannas. In high rainfall and high yield environment (Zaria), wider sowing window exists for the whole of July, but delayed planting to August could result in relatively low crop yield, irrespective of variety used. High rainfall in Puba Vidau did not necessarily result in high and stable yield likely due to soil constraints including high clay content and potential water saturation. Delayed sowing consistently resulted in low and variable yields due to cessation of rain during the key phenological development (flowering and grain filling). This study could fill the knowledge gap in understanding optimal cowpea management opportunities needed to maximize productivity and strengthen cropping resilience.

CRedit authorship contribution statement

Kamaluddin T. Aliyu: Writing – original draft, Supervision, Methodology, Formal analysis. **Lucky O. Omoigui:** Writing – review &

editing, Writing – original draft, Methodology, Investigation. **Jibrin M. Jibrin**: Validation, Supervision, Methodology. **Abdullahi I. Tofa**: Writing – review & editing, Writing – original draft, Methodology, Investigation. **Reuben Solomon**: Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Data curation. **Osagie B. Eseigbe**: Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Data curation. **Ismail I. Garba**: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis. **Jenneh F. Bebeley**: Methodology, Investigation, Formal analysis. **Musibau A. Adeleke**: Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Kamara Alpha**: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Helen P. Jerome**: Writing – review & editing, Methodology, Formal analysis.

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Declaration of Competing Interest

We declare that we have no conflicting interest and the manuscript has only been submitted to this journal for consideration for publication. All Authors have agreed to submit the manuscript for publication

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.fcr.2025.109988](https://doi.org/10.1016/j.fcr.2025.109988).

Data availability

Data will be made available on request.

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