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Establishing Optimal Planting Windows for Contrasting Sorghum Cultivars across Diverse Agro-Ecologies of North-Eastern Nigeria: A Modelling Approach

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Abstract: In the context of climate change, the sowing date and cultivar choice can influence the productivity of sorghum, especially where production is constrained by low soil fertility and early terminal drought across the challenging agro-ecologies of north-eastern Nigeria. Planting within an optimal sowing window to fit the cultivar's maturity length is critical for maximizing/increasing the crop yield following the appropriate climate-smart management practices. In this study, the APSIM crop model was calibrated and validated to simulate the growth and yield of sorghum cultivars with differing maturing periods sown within varying planting time windows under improved agricultural practices. The model was run to simulate long-term crop performance from 1985 to 2010 to determine the optimal planting windows (PWs) and most suitable cultivars across different agro-ecological zones (AEZs). The performance of the model, validated with the observed farm-level grain yield, was satisfactory across all planting dates and cropping systems. The model predicted a lower mean bias error (MBE), either positive or negative, under the sole cropping system in the July sowing month compared to in the June and August sowing months. The seasonal climate simulations across sites and AEZs suggested increased yields when using adapted sorghum cultivars based on the average grain yield threshold of ≥1500 kgha^{-1} against the national average of 1160 kgha^{-1}. In the Sudan Savanna (SS), the predicted optimum PWs ranged from 25 May to 30 June for CSR01 and Samsorg-44, while the PWs could be extended to 10 July for ICSV400 and Improved Deko. In the Northern Guinea Savanna (NGS) and Southern Guinea Savanna (SGS), the optimal PWs ranged from 25 May to 10 July for all cultivars except for SK5912, for which predicted optimal PWs ranged from 25 May to 30 June. In the NGS zone, all cultivars were found to be suitable for cultivation with exception of SK5912. Meanwhile, in the SGS zone, the simulated yield below the threshold (1500 kgha^{-1}) could be explained by the sandy soil and the very low soil fertility observed there. It was concluded that farm decisions to plant within the predicted optimal PWs alongside the use of adapted sorghum cultivars would serve as key adaptation strategies for increasing the sorghum productivity in the three AEZs.

Keywords: adaptation; agro-ecological zones (AEZs); APSIM; adapted sorghums; optimal planting window

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1. Introduction

Nigeria is the largest producer of sorghum in West Africa, accounting for about 65–70% of the total sorghum production in the region [1]. Its sorghum production in 2018 was 6.9 million tonnes, accounting for 50% of the total cereal production and occupying about 45% of the total land area devoted to cereal crop production in Nigeria [2]. The production of sorghum in Nigeria, where it is predominantly cultivated in the northern region, has increased overall [3], reaching some seven million tons in 2021, with an average yield of 1160 kgha^{-1} meaning that it is one of the main crops for the country. The increase in production is associated with the dissemination of improved sorghum cultivars that are tolerant to drought and Striga [4]. These cultivars have been promoted through several initiatives by the Federal Government of Nigeria and other development partners. Landraces have long been recognized as a source of traits for local adaptation, stress tolerance, yield stability, and seed nutrition [5]. The long-term selection under variable and low-input environments has resulted in high crop diversity in landraces. The environmental factors contributing to production constraints and low yields include low fertility soils, the length of the growing periods, drought, and water-logging, as well as biotic stresses such as *Striga* parasitism and diseases attacking the foliage, stems, and/or grain [6]. Photoperiod sensitivity is an important trait of West African sorghum germplasm that allows farmers to cope with variations in the planting date (PD) and adapt to environmental constraints [7,8]. The triggering of flowering by day length effectively serves to synchronize the final developmental stages with the end of the rainy season [9]. A major problem in rainfed agriculture in semi-arid regions characterized by short rainy season, occasionally accompanied by in-season drought, is how to determine the optimum sowing date [10]. The delays in the onset of the rainfall, drought, unpredictable periodic dry spells, and shortened rainfall seasons have led to a slight shift in the traditionally recommended sorghum planting dates [11].

Crop management must not only adapt to changing climatic conditions to maintain sufficient production but must do so in a way that reduces greenhouse gas emissions as much as possible—i.e., cropping systems must be climate smart [12]. Transformative changes for climate-smart agriculture must include changes to crops, management, and systems that build resilience to climate change impacts and emit relatively low emissions [13]. Although limited data exist, the available studies have shown that the cultivation of sorghum is relatively low in agricultural emissions compared to other crops [14]. Despite the importance of understanding the potential of sorghum to contribute to a climate-smart future and to food security in Nigeria, as well as in the dryland West Africa region, the promotion of productivity-enhancing technologies (climate-smart strategies) among the farmers is becoming imperative for increasing productivity. Therefore, the choice of a sorghum cultivar with an appropriate planting date should be combined such that the productivity of the sorghum would be optimal when the flowering occurs at least 20 days before the terminal drought in the cropping season [7,15,16]. Thus, matching the phenology to the given biotic and abiotic conditions is a prerequisite for good varietal adaptation to a given environment [7]. Crops adapt to diverse environments through considerable plasticity of phenology, the main determinant of which is rainfall [17] in the semi-arid region; meanwhile, the temperature has a stronger effect in the temperate region. “Manipulating this climatic factor would require adequate knowledge of planting dates so as to accurately synchronize rainfall incidences with crop development” [18].

In north-eastern Nigeria, as applies to other semi-arid regions, the length of the growing period (LGP) is mainly a function of the date of the first rains [19,20], which is delayed as we moved northward and varies widely from year to year. The region is prone to climatic risk, and a good knowledge of the cultivar development cycles relative to the planting date is required for improved productivity. However, with the variable onset and distribution of rainfall as well as the frequent occurrence of drought within the growing season, the farmers’ choice of cultivars would depend mainly on their knowledge of the crop’s phenology and yield potential in relation to the local characteristics of the wet season [21,22].

In West Africa’s semi-arid agro-ecology, favourable conditions for sorghum cultivation usually extend from May to November [20]. Thus, floral initiation takes place under decreasing day length, and the growth duration of photoperiod-sensitive cultivars will be shortened when sowing is delayed [23]. Although photoperiod sensitivity benefits sorghum, in that flowering takes place at a relatively fixed calendar date and allows it to mature after the rains end, despite highly variable sowing dates [24], a high degree of poor grain filling is encountered among the late-planted and late-maturing varieties that run out of water if the sorghum is planted too late in the season [25,26]. In this situation, matching suitable cultivars with their optimal planting windows becomes an important management option. In addition, knowing the extent to which planting can be delayed and the likely yield penalty due to later than the optimal planting [27] is important for increasing the productivity of sorghum in a semi-arid environment.

In semi-arid environments, the planting date decision is important not only because of its effect on yield [28], but also because of the need to minimize the risk of establishment failures and ensure the availability of water for unrestricted plant growth and transpiration [17]. Recommendations concerning the planting dates of crops are usually based on agronomic field experiments that are specific to the fields and regions [29]. The majority of such trials cannot be temporally and spatially replicated across diverse agro-ecologies because of seasonal variations. The determination of the optimum sowing dates for sorghum by field experimentation entails repetition over long periods in order to capture the seasonal variability in the rainfall with the varying photoperiod sensitivity cultivars available. Thus, cropping system models (CSMs) have been a proven methodology for understanding the interactions between climate, soils, farming systems, and management [30,31]. These models, therefore, remain important diagnostic tools for decision-making, not only to capture the effects of variability of the rainfall and edaphic factors on crop productivity, but also to suggest sowing date rules and other crop management strategies for better and more sustainable agriculture [31,32]. Cropping system models such as Agricultural Production Systems sIMulator, APSIM [33,34], describe the dynamics of crop growth, soil water, soil nutrients, and plant residues as a function of climate, cropping history, and soil/crop management in a daily time step. Through the linking of crop growth with soil processes, APSIM is particularly suited for the evaluation of the likely impacts of alternative management practices such as varying planting dates on soil resources and crop productivity. The model has been used intensively in the search for strategies for more efficient production, improved risk management, crop adaptation, and sustainable production [33,35,36]. This work, therefore, seeks to establish the response of diverse sorghum cultivars to different planting windows in the three major agro-ecologies of north-eastern Nigeria. To achieve this, the following objectives were set: (i) evaluate the performance of the APSIM model for simulating the contrasting sorghum cultivars under different management systems, soils, and rainfall patterns; (ii) apply the model to determine the optimal PWs and adapted sorghum cultivars for higher grain yield and resilience in order to minimize crop failure across sites and AEZs.

2. Materials and Methods

2.1. Model Calibration (Experiments, Data Collection, Procedure for Model Calibration and Evaluation)

The experimental data used for the calibration were principally generated from on-station field experiments conducted between 2016 and 2018 under optimal conditions (i.e., no water and nitrogen stress) in two AEZs (Abuja, Southern Guinea savannah, and Kano, Sudan savannah) in northern Nigeria. The experiment was designed to evaluate the effects of sowing dates and nutrient responses on contrasted sorghum cultivars. In Abuja, the experiment was established at the International Institute of Tropical Agriculture (IITA) field station (Latitude 9.16° N, and Longitude 7.35° E), while, in Kano, the experiment was established in two locations: (i) the Bayero University Kano (BUK) Teaching and Research Farm (Latitude 12.98° N and Longitude 9.75° E) and (ii) the ICRISAT research field situated within the Institute for Agricultural Research (IAR) station, Wasai Village, Minjibir (Latitude 12.17° N and Longitude 8.65° E). The details of the experiment and the agronomic data collected have been reported [37,38]. Among the 20+ sorghum cultivars commercially available in Nigeria, five contrasting sorghum cultivars that were considered to be widely cultivated were tested based on their breeding selection history for phenology, photoperiod sensitivity, and grain yield productivity. According to a national cultivar report [39,40], ICSV-400 is an early maturing cultivar (85–90 days), is photoperiod-insensitive, and has a yield potential from 2.5 to 3.5 t/ha; Improved Deko is medium maturing (90–110 days) and has a low photoperiod sensitivity and a yield potential from 3.5 to 4.0 t/ha; Samsorg-44 and CSR01 are medium maturing and medium photoperiod-sensitive and have yield potential from 2.0 to 2.5 t/ha; and SK5912 is late maturing (165–175 days) and highly photoperiod-sensitive, with a potential yield of 2.5–3.5 t/ha when grown under optimum conditions.

The daily weather was obtained from an automatic weather station (AWS) installed within a 2 km radius of the experiment for the corresponding years of the experiment and was used for calibration. The parameters include the daily maximum and minimum temperature, the solar radiation, and the rainfall. Management practices such as planting dates, sowing depth, plant density, type and amount of fertilizer applied in form of NPK, and tillage (type, depth, and fraction of above-ground materials incorporated) were recorded and used for the model setup and simulation. The soil samples were taken before planting at each experimental site and were analysed for their physical and chemical properties. The agronomic data, such as dates of flowering and maturity, leaf number per plant, leaf area index (LAI), yield, and final biomass collected [4], were used to determine the cultivar-specific parameters.

The calibration of the APSIM-sorghum module was implemented within the APSIM 7.10 framework based on the phenology, morphology, yield, and aboveground biomass data described earlier. The model APSIM requires a number of inputs, which include the cultivar type, crop management practices/information, soil properties, and daily weather records (rainfall, minimum temperature, maximum temperature, and solar radiation). Crop development follows a thermal time approach with a reported base (T_b) and optimal (T_{opt}) and maximum (T_m) temperatures of 11, 32, and 42 °C [41,42]. The thermal time target for the phase between emergence and panicle initiation is also a function of the day length, and its duration, when divided by the plastochron (°C degrees per leaf), determines the total leaf number. The total leaf number multiplied by the phyllochron (°C d per leaf) determines the thermal time to reach the flag leaf stage, which is thus an emergent property of the model. For parameterizing the genetic coefficients of previously undefined sorghum cultivars, the phenological and morphological stages were based on a combination of observed data and simulation to obtain a yield and above-ground biomass (AGB) that fell within the predefined error limits for each cultivar. Following this method, all coefficients were optimized for further simulation as defined in Table 1. Thereafter, the performance of the model in simulating the phenology (days to flowering and maturity), morphology (leaf number per plant and maximum leaf area index (Max_LAI)), grain yield, and AGB were compared with the observed values and assessed using mean bias error (MBE), root mean square error (RMSE), normalized root mean square error ($RMSE_n$) and the traditional R^2 regression statistic (least-squares coefficient of determination) [43]. $RMSE_n$ gives a measure (%) of the relative difference between the simulated versus observed data. The simulation was considered excellent with $RMSE_n$ < 10%, good if 10–20%, acceptable or fair if 20–30%, and poor >30% [44].

Table 1. Genetic coefficients of sorghum cultivars calibrated in the APSIM-sorghum model.

Description of Parameter	Unit	ICSV400	Impr. Deko	CSR01	Samsorg-44	SK5912	Calibration Method (A/B)
Thermal time from emergence to end of juvenile	°C days	180	210	100	100	100	A
Thermal time from end of juvenile to floral initiation	°C days	160	100	100	100	120	A
Photoperiod slope	°C/hour	150	200	500	550	600	A

Table 1. *Cont.*

Description of Parameter	Unit	ICSV400	Impr. Deko	CSR01	Samsorg-44	SK5912	Calibration Method (A/B)
Thermal time from flag leaf to flowering	°C days	170	170	100	100	150	A
Thermal time from flowering to start of grain filling	°C days	80	80	80	80	80	B
Thermal time from flowering to maturity	°C days	560	560	460	500	450	A
Leaf appearance rate (leaf app rate 1)	°C d/leaf	41	56	56	56	56	[31]
Leaf appearance rate (leaf app rate 2)	°C d/leaf	20	28	28	28	28	[31]
Radiation use efficiency(RUE)	g/MJ	1.25	1.25	1.35	1.35	1.65	A
Head grain number determination	g/grain	0.00083	0.0088	0.00083	0.00083	0.0088	A
Maximum grain filling (MaxGFrate)	mg/grain/day	0.09	0.03	0.05	0.05	0.09	A

A: Manual tuning of parameter values; B: Model defaults values; [31] means the parameter calibrated based on the value reported.

$$MBE = 1 - \frac{\left(\sum_{i=1}^{n} Oi - \sum_{i=1}^{n} Pi\right)}{\sum_{i=1}^{n} Oi} \tag{1}$$

$$RMSE = \left[\frac{\sum_{i=1}^{n} (Pi - Oi)^2}{n}\right]^{0.5} \tag{2}$$

$$RMSEn\ \% = \left[\frac{\sum_{i=1}^{n} (Pi - Oi)^2}{mean\ of\ observed\ data}\right]^{0.5} \times 100 \tag{3}$$

where n is the number of observations, Pi is the predicted value for the ith measurement and Oi is the observed value for the ith measurement, and O and P represent the mean of the observed and predicted values for all of the parameters studied.

2.2. Model Validation (Experiments, Data Collection, Procedure for Model Validation, and Evaluation)

An independent dataset used for model validation was generated from multi-locational on-farm trials for improved sorghum production technology conducted through the farmers' participatory program between 2013 and 2017. The dataset revealed three distinct cropping systems (intercropping, mixed cropping, and sole cropping) comprising a range of production technologies, including improved sorghum varietal demonstration, seed dressing techniques, conservation agriculture (minimum tillage and conventional tillage), and fertilization strategies aimed at increasing sorghum productivity at the farm level. The additional datasets were obtained from the ICRISAT breeding program from on-farm varietal experiments tested across northern Nigeria spanning four agroecological zones (Sahelian, Sudan Savanna, Northern Guinea, and Southern Guinea Savanna). All the data used are well-documented and include information about basic agronomic management practices such as the sowing date, fertilizer application rate, time of application, planting density, reference geographical coordinates of each farm plot/community, final grain yield, and stalk yield for the five (5) selected and calibrated sorghum cultivars. In addition, variations in the planting date across farms and cultivars were grouped under three months (referred to as "sowing month"), which revealed that 92% of farmers planted in the months of June and July, and only 8% of the farmers sowed in the month of August. Weather data were generated using the downscaled Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) rainfall at a 5.5 km resolution and merged with NASA Power data (temperatures and solar radiation) from the database for Climatology Resource for Agroclimatology, National Aeronautics and Space Administration (NASA) (http://power.larc.nasa.gov, assessed on 25 April 2019) for the corresponding farm's reference coordinates.

Two sources of soil information were obtained for soil parametrization. The first included field-measured soil characteristics and combined the reconnaissance soil survey of Nigeria reported in 1990 and the soil analysis by the Taking Maize Agronomy to Scale in Africa (TAMASA) project in Kano, Kaduna, and Katsina States, respectively. The second soil data source was downscaled ISRIC (International Soil Reference and Information Centre) soil data in 10 × 10 km grids, with the profile layers (in cm) being 5, 15, 30, 60, 100, and 200, used for the corresponding farm's references coordinates. After bias correction of the gridded dataset using the available soil measurement, the soil information was extracted from the ISRIC database [45] for each farm's reference coordinates (the nearest grid point) to run the simulation across the locations. Furthermore, R scripts were developed to (i) append the CHIRPS and NASA power data together and convert each location into a format readily ingestible by APSIM; and (ii) remap the ISRICS gridded soil from 5 cm to 15 cm for the top soil layer as required by APSIM, and then convert these soils into an APSIM SOIL readable format. Following the calibrated cultivar-specific coefficients, an excel executable file was developed that incorporated the management practices, cultivar name, soil, and weather records for the corresponding farm/plot alongside the reported observed grain yield. From the spreadsheet executable file, we created a 3266 APSIM simulation setup that defined different sowing dates, planting densities, and fertilizer applications as reported for the five sorghum cultivars. The model's simulated and observed value was evaluated only for grain yield across the sowing and cropping system using the mean bias error (MBE) and root means square error (RMSE).

2.3. Bias Correction Methods: Daily Observed Rainfall Versus Gridded Rainfall Data (CHIRPS)

Data from nine (9) rainfall observation stations in northern Nigeria with long-term records (1983–2006) were obtained from the climatological unit of the Nigerian Meteorological Agency (NIMET). The Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data are satellite-based rainfall products with relatively high resolutions (0.05°) and quasi-global coverage (50° S-50° N) for their daily, pentadal, and monthly precipitation datasets [46]. The data were downscaled over the Nigeria grids and extracted for the reference coordinates of the 9 daily observed rainfall stations and 288 different farms coordinates used in the simulations. The bias correction of the gridded data using station-observed data has been shown to increase its applicability to daily time-step agricultural modelling [47]. Two techniques (linear scaling (LS) and empirical quantile mapping (EQM)) were applied to correct the biases in the dataset during validation process. The LS technique shows better accuracy than EQM and replicated the daily observed rainfall data following the study by [48,49].

2.4. Long-Term Simulations of the Contrasted Sorghum Cultivars under Varying Sowing Windows

The simulations were performed across 33 selected sites in Adamawa and Borno States in north-eastern Nigeria for the five calibrated sorghum cultivars. The sites represent the three agroecological zones of the SS, NGS, and SGS (Table 2). The SS has a long dry season followed by a mono-modal rainfall pattern with a distinct rainy season (May–October) and characterized by a high mean temperature (28–32 °C), short growing season (90–110 days), and low rainfall ranging from 600 to 800 mm [50]. Soils in the SS of Nigeria are highly weathered and fragile with low clay content [51]. The dominant soil class of the site is Alfisol, according to the USDA soil taxonomy [52]. In the NGS, the length of the growing period is between 151 and 180 days [53]. It has a mono-modal rainfall distribution ranging from 900 to 1000 mm annually, and its mean temperatures vary from 28 to 40 °C [54]. According to the world reference baseline, its soils are classified as leached ferruginous tropical soils with high clay content and overlying drift materials [55]. The dominant soil types found in the zone are Alfisols and Entisols, according to the FAO classification. In the SGS, the average maximum temperature in the growing season ranges from 26 to 28 °C, whereas the minimum temperature ranges between 18 and 22 °C [56,57]. The rainfall pattern is mono-modal, with an annual rainfall between 1000 mm and 1524 mm and spread over the 181–210 days that define the growing season [52,56]. The soils in this zone have been identified mainly as Lithosols, Ferralic combisols, Feric acrisols, Oxic haplustalfs and Luvisols [58].

Table 2. Summary of the selected sites for model application of sorghum cultivars under varying planting windows.

S/No	State	LGA	Site	AEZ	Longitude (N)	Latitude (E)
1	Adamawa	Hong	Dulmava	SS	12.9824	10.3014
2		Gombi	Guyaku	SS	12.6634	10.3459
3		Demsa	Mbula Kuli	NGS	12.3016	9.45745
4		Girei	Wuroshi	NGS	12.6164	9.46866
5		Girei	Daneyel	NGS	12.514	9.54761
6		Gombi	Tawa	NGS	12.6856	10.1691
7		Guyuk	Chikila	NGS	11.9719	9.77237
8		Guyuk	Lakumna	NGS	11.9897	9.92083
9		Hong	Hushere Zum	NGS	13.0807	10.1038
10		Numan	Bare	NGS	12.1108	9.5843
11		Numan	Kikan_Kodomti	NGS	11.9878	9.46081
12		Shelleng	Jonkolo-Lama	NGS	12.178	9.89965
13		Shelleng	Lakati-Libbo/	NGS	12.2502	9.69541
14		Song	Sabon Gari	NGS	12.5935	9.84049
15		Song	Suktu	NGS	12.4248	9.63746
16		Demsa	Nassarawo Demsa	SGS	12.1501	9.29625
17		Yola North	Yelwa-Jambore	SGS	12.5046	9.26165
18		Yola South	Fufure	SGS	12.6504	9.1736
19	Borno	Bayo	Balbaya	SS	11.7648	10.5848
20		Bayo	Briyel	SS	11.6497	10.371
21		Bayo	Jara-Dali	SS	11.7316	10.2759
22		Biu	Buratai	SS	12.4158	10.7675
23		Biu	Kabura	SS	12.2653	10.7392
24		Biu	Mathau	SS	12.1097	10.7214
25		Biu	Tum	SS	12.4881	10.8228
26		Hawul	Kwajaffa	SS	12.4831	10.5167
27		Hawul	Puba Vidau	SS	12.1879	10.5224
28		Hawul	Sakwa Hema	SS	12.3894	10.3867
29		Kwayakusar	Kurbo Gayi	SS	11.9575	10.384
30		Shani	Lakundum	SS	12.0506	10.0556
31		Shani	Gwaskara	NGS	12.158	10.2271
32		Kwayakusar	Bila Gusi	NGS	12.0476	10.5192
33		Shani	Kubo	NGS	12.0853	10.14

LGA—Local Government Area, AEZ—Agro-ecological zone; SS—Sudan Savannah, NGS—Northern Guinea savannah, SGS—Southern Guinea savannah.

The soil parameters used were obtained from on-site soil characterization using geospatial buffering points at a 20 km radius using an ArcGIS map of the reference indicating the sites/LGAs. For soil characterization and soil sampling, profile pits were dug in the 33 selected sites in Adamawa and Borno States. The profiles and soil types were classified using the FAO guidelines [59]. All laboratory analyses were carried out at the Analytical Services Laboratory of IITA. The total soil organic carbon (total C) was measured using a modified Walkley and Black chromic acid wet chemical oxidation and spectrophotometric method [60]. The total nitrogen (total N) was determined using a micro-Kjeldahl digestion method [61]. The soil pH in water (S/W ratio of 1:2.5) was measured using a glass electrode pH meter and the particle size distribution, following the hydrometer method [62]. The available phosphorus was extracted using the Bray-1 method [63]. The phosphorus in the extract was determined calorimetrically according to the molydo-phosphoric blue method, using ascorbic acid as a reducing agent. K was analysed based on the Mehlich 3 extraction procedure [64]. In Adamawa State, most of the topsoils were coarse-textured with higher sand content. In all, 72% had sandy loam, 17% had clay, and 11% had a sandy clay loam texture (Table 3). The soil pH for the selected communities in Adamawa ranged from 5.9 (Jonkolo-Lama in Shelleng) to 8.0 (Fufure). More than 55% of the soils had pH values for ideal plant growth, indicating neutral (6.1–6.5) to alkaline (8.1–8.3) soil reactions. The soil organic carbon (OC) content in ranged from 0.22% in Daneyel and Suktu to 0.90% in the Guyuk area. The distribution of soil in the study areas revealed that most of the soils had low (0.4–1.0%) OC levels. The total soil N content in the soils ranged from very low (<0.05%) to low (0.06–0.1%), with 67% of the study locations falling within the very low N class and 33% of the study sites indicating low N classes. The soil available P varied across the locations, with very low P (<3.0 mg kg^{-1}) at Woroshi, Tawa, Chikila, Lakumna, Dulmava, Hushere-Zum, Jonkolo-Lama, Sabon-Gari, and Yelwa-Jambore. Low soil available P (3–7 mg kg^{-1}) was found in Demsa-Nassarawa, Bare, Lakati-Libbo, and Suktu, while high P (11–32.1 mg kg^{-1}) content was found in Mbula Kuli, Kikan_Kodomti and Fufure. The results showed that 50% of the study sites fell within the very low P fertility class, 28% of the sites fell within the low P fertility class, and 22% of the sites fell within the high P fertility class. The exchangeable K level across the sites ranged from low to high values, with 22% low (<0.15 $cmol^+$ kg^{-1}), 44% moderate (0.16–0.3 $cmol^+$ kg^{-1}), and 33% high (>0.3 $cmol^+$ kg^{-1}).

Table 3. Physical and chemical properties used for model applications in Adamawa State.

Site	Profile Depth (cm)	BD (g/cm^3)	OC (%)	Sand (%)	Silt (%)	Clay (%)	pH (in H_2O)	N (%)	Meh. P (ppm)	K cmol/kg
Mbula-Kuli	0–200	1.76	0.84	59	23	18	7.8	0.06	32.1	0.5
Demsa-Nassarawo	24–180	2.18	0.66	65	15	20	8.3	0.06	3.8	0.89
Daneyel	31–200	1.76	0.22	81	7	12	7.0	0.01	10.9	0.3
Woroshi	14–94	2.16	0.54	65	19	16	6.4	0.04	1.17	0.36
Guyaku	19–120	1.7	0.35	79	9	12	6.6	0.03	2.14	0.22
Tawa	15–127	1.79	0.62	75	13	12	6.7	0.05	3.38	0.21
Chikila	30–180	2.18	0.90	15	19	66	8.5	0.08	2.55	0.13
Lakumna	20–200	1.77	0.90	25	23	52	7.3	0.10	1.59	0.65
Dulmava	27–201	1.82	0.51	67	15	18	7.5	0.06	1.03	0.17
Hushere-Zum	41–205	1.93	0.46	80	8	12	6.3	0.03	2.41	0.40
Bare	25–200	1.62	0.35	74	9	17	6.6	0.02	4.07	0.20
Kikan_Kodomti	22–200	1.76	0.66	71	9	20	7.3	0.04	13.7	0.20
Lakati-Libbo	27–200	1.83	0.30	78	9	13	7.4	0.01	5.04	0.20
Jonkolo-Lama	15–200	2.06	0.33	78	10	12	5.9	0.02	0.89	0.14
Sabon-Gari	31–200	1.73	0.66	25	33	42	6.2	0.04	1.45	0.4
Suktu	35–210	2.08	0.22	71	11	18	6.3	0.03	6.56	0.20
Yelwa-Jambore	24–155	2.19	0.4	77	11	12	6.5	0.03	1.8	0.09
Fufure	20–145	1.98	0.54	65	17	18	8.0	0.02	32.1	0.10

BD = bulk density, OC = organic carbon content, N = percent Nitrogen, Meh P = Available Phosphorus, and K = potassium.

Similarly, in Borno state, the majority of the soils were coarse-textured with higher sand content. Out of the 15 sites, 47% had sandy loam, 27% had clay, and 26% had a silt loamy sand texture (Table 4). The soil pH of water for the communities in Borno State ranged from 6.1 to 8.4. More than 70% of the soils had neutral reactions (6.6–7.8), which is the ideal condition for plant growth. The soil OC content in the state ranged from 0.12% to 0.78%. Eight (8) communities equivalent to 53% of the study area had very low OC (<0.4%)

levels. The total soil N content in the soils ranged from very low to low, with a very low (<0.05%) status found in the Balbaya, Bila Gusi, Briyel, Buratai, Gwaskara, Jara-Dali, Kubo, Kurba, Mathau, Puba Vidau, Sakwa-Shema, and Tum communities, while the Kwaya Bura, Kwajaffa, and Lakundum communities fell within the low (0.06–0.1%) N fertility class. With the exception of Gwaskara and Lakundum, the top soil available P at all the locations fell within very low (<3.0 mg kg^{-1}) fertility class. The exchangeable K levels were 7% low (<0.15 cmol^{+} kg^{-1}), 33% moderate (0.16–0.3 cmol^{+} kg^{-1}), and 60% high (>0.3 cmol^{+} kg^{-1}) across the sites.

Table 4. Physical and chemical properties used for model applications in Borno State.

Site	Profile Depth (cm)	BD (g/cm^3)	OC (%)	Sand (%)	Silt (%)	Clay (%)	pH (H_2O)	N (%)	Meh. P (ppm)	K cmol/kg
Balbaya	9–200	1.59	0.29	83	7	10	6.1	0.01	1.03	0.0
Briyel	15–200	1.32	0.39	19	29	52	8.4	0.02	2.69	0.4
Jara-Dali	8–200	1.55	0.33	51	13	36	6.6	0.02	1.72	0.3
Buratai	29–150	1.63	0.17	74	8	18	7.6	0.02	2.69	0.6
Kwaya Bura	22–101	1.36	0.78	36	38	26	7.1	0.06	0.89	9.0
Mathau	12.0–94	1.62	0.12	90	0	10	7.4	0.01	2.83	0.8
Tum	12–200	1.40	0.19	28	24	48	7.4	0.01	1.17	0.6
Kwajaffa	30–110	1.31	0.54	16	27	57	7.4	0.06	2.28	0.7
Puba Vidau	10–200	1.32	0.4	18	19	63	8.3	0.02	0.89	0.6
Sakwa Hema	15–170	1.57	0.52	74	9	17	7.0	0.04	0.76	0.1
Bila Gusi	80–200	1.59	0.48	67	15	18	6.5	0.02	2.14	0.1
Kurba Gayi	10–200	1.60	0.32	75	9	16	7.2	0.01	1.03	0.1
Gwaskara	19–200	1.57	0.34	72	13	15	7.1	0.01	11.5	0.1
Kubo	33–200	1.54	o.46	64	13	23	7.3	0.02	1.31	0.8
Lakundum	16–200	1.52	0.73	72	10	18	7.3	0.07	13.6	9.0

BD = bulk density, OC = organic carbon content, N = percent Nitrogen, Meh P = Available Phosphorus and K = potassium.

The long-term (1985–2010) weather data used in the model application was a combination of downscaled CHIRPS (for daily rainfall) and the NASA database for Climatology Resource for Agroclimatology (for minimum and maximum air temperature and solar radiation respectively). The simulations were set up to run at different planting windows using the fertilizer N at the national fertilizer rate of recommendation (NPK 60:30:30 kghakgha^{-1}) for sorghum. In the model, 30 kg N were applied at sowing (DAS), with Urea (46% N) top dressed at 30 kg of N ha^{-1} at 30 DAS. The simulation considered an optimum population to be at a 75 cm inter-row by 30 cm intra-row spacing given 44,444 hills/ha against the farmer's lower rate of 22,222 hills/ha. Based on expert knowledge and a previous study [22] that found that the sowing period for sorghum across the three agro ecologies stretches over 60 days, we divided the entire sowing period into four equal planting windows to capture the photoperiod sensitivity of the cultivars. The model was set to consider four (4) planting windows as follows: 16–31 May (PW1), 1–15 Jun (PW2), 16–30 Jun (PW3), and 1–15 Jul (PW4), respectively. In addition, rule-based sowing within the sowing window was applied (cumulative rainfall of 20 mm in 3 rainy events) and implemented at the 33 sites. The sowing depth was set to 5 cm, with a sowing density of 4.5 plant m^2. Considering the farmers' practices in the region, a non-successive simulation (single season, non-rotation mode) was adopted, which implies that the water, organic matter, nitrogen, and phosphorus were reset a few weeks before the start of the growing season.

The optimal window for the sowing dates of the sorghum cultivar was based on the average simulated grain yield over the 26-year period and across the sites in each AEZ. Also, the coefficient of variation (CV%), as the ratio of the standard deviation to the mean simulated grain yield, was used to assess the suitable cultivar for each site and AEZ. The level of variability (high or low percentage) determined whether the cultivar had a high or low suitability for the site based on a mean grain yield of $\geq$1500 kgha^{-1} as the threshold.

The threshold was determined as a break-even yield that farmers can produce for marginal economic benefit as described by [22]. The potential evapotranspiration based on the Penman-Monteith equation [37] in the APSIM model was computed as the addition of the simulated soil evaporation and crop transpiration, and, from that, the water use efficiency for the grain yield (WUE_{grain}) was calculated.

3. Results

3.1. Model Performance

As depicted in Table 1, there were differences in the cultivar-specific coefficients across the new sorghum cultivars, particularly in the thermal time that defined the crop vegetative and growth. ICSV400 and Improved Deko had a shorter thermal time requirement (in degree days) to attain the end of the juvenile stage compared to CSR01, Samsorg-44, and SK5912, respectively. Both cultivars (ICSV400 and Improved Deko) were originally bred for drought conditions, which could allow them to serve as a drought escaping mechanism compared to the other cultivars. Also, the calibrated photoperiod slope varied from 11.5 °C/h to 600 °C/H, indicating a shorter degree/hour for low photoperiod sensitivity cultivars such as ICSV400 and improved Deko, while a longer degree/hour was calibrated for the medium and high photoperiod sensitivity cultivars. The thermal time from flowering to physiological maturity above a base temperature of 10 °C was 560 °C days for ICSV400 and improved Deko, indicating a higher value than the degree days of CSR01 (460 °C days), Samsorg-44 (500 °C days), and SK5912 (450 °C days), respectively. The cultivar genetics coefficients for leaf appearance rate followed two steps, i.e., leaf appearance to the development of most leaf ligules (leaf_app_rate 1) and to the last leaf ligule (leaf_app_rate 2). The calibrated values (56 °C d/leaf and 28 °C d/leaf) were the same for all of the varieties except for ICSV400. These values justified the increase in the leaf number (>20) per plant for most West African sorghum cultivars that are photoperiod sensitive.

The performance of the model, presented in Table 5, shows that the simulated days to 50% flowering and to physiological maturity were good and reproduced the observed values with a mean bias error (MBE) ranging from −4 to 4 days (50% flowering) and from 1 to 2 days (physiological maturity). The RMSE of the mean observed estimate of ≤10% for all the cultivars confirmed the robustness of the predictions. The model's adjustment of the leaf appearance rate for leaf ligules helps to get an accurate total leaf number (TLN) per plant close to the observed. The estimates of the MBE varied from one to five leaves, and RMSE (of the mean observed) ranged from a high model accuracy (6.4% for improved Deko) to a fairly low accuracy (26.2% for Samsorg-44) for TLN.

Table 5. Statistical evaluation of simulated phenology and morphological traits (LAI and total leaf number/plant) of contrasted sorghum cultivars calibrated from experiment conducted under optimum conditions in Southern Guinea and Sudan Savannah AEZs.

Parameters/ Cultivar	Unit	N	MBE	RMSE		Observed Range	Observed Mean
				Absolute Value	% of Mean Observed		
ICSV-400							
50% Flowering	DAP	11	−1	4	5.4	62–75	68
Physiological Maturity	DAP	11	2	5	4.6	90–106	97
LAI-max	m^2/m^2	11	−0.2	0.8	32.4	1.8–3.0	2.3
Leaf number		4	3.4	3.5	20.5	16–18	17
Improved Deko							
50% Flowering	DAP	7	−4	6	7.9	75 95	84
Physiological Maturity	DAP	7	1	6	5.0	101–122	110
LAI-max	m^2/m^2	7	0.6	0.8	27.0	2.0–3.3	2.5
Leaf number		4	0.4	1.2	6.4	16–19	18

Table 5. *Cont.*

Parameters/ Cultivar	Unit	N	MBE	RMSE		Observed Range	Observed Mean
				Absolute Value	% of Mean Observed		
Samsorg-44							
50% Flowering	DAP	4	1	3	3.0	85–114	99
Physiological Maturity	DAP	4	2	4	3.2	112–140	126
LAI-max	m^2/m^2	4	0.2	0.7	26.6	2.2–3.4	3.0
Leaf number		4	5.1	5.2	26.2	19–23	20
CSR01							
50% Flowering	DAP	8	2	8	8.4	84–112	95
Physiological Maturity	DAP	8	1	7	6.1	111–139	123
LAI-max	m^2/m^2	8	0.3	0.4	14.7	2.3–3.7	3.0
Leaf number		8	4	4.1	19.5	19–24	21
SK5912							
50% Flowering	DAP	4	4	5	4.4	95–122	108
Physiological Maturity	DAP	4	2	4	3.0	122–149	135
LAI-max	m^2/m^2	4	0.3	0.6	20.7	2.0–3.3	2.5
Leaf number		4	3.8	4.0	17.6	20.4–25.4	23

N—Number of observations; LAI-max: maximum leaf area index measured during growth; MBE = positive implies over-simulated mean observed; negative implies under-simulated the mean observed value.

The simulated and observed maximum Leaf Area Index (Max_LAI) for all cultivars agrees well with RMSE (% of mean observed), indicating high accuracy for CSR01 and SK5912, low accuracy for improved Deko and Samsorg-44, and very low accuracy for ICSV400. The grain yield and total biomass were acceptably simulated for the contrasted sorghum cultivars within the bounds of statistical errors (Figure 1). For grain yield (Figure 1a), CSR01 had the lowest MBE of −48 kghakgha^{-1}, which under-predicted the observed mean, followed by ICSV-400 (103 kghakgha^{-1}) and improved Deko (114 kghakgha^{-1}), while the highest yield (279 kgha^{-1}) was shown by the cultivar Samsorg-44. The relative RMSE ranged from high accuracy for SK5912 (9.2%) to very low accuracy for ICSV-400 (28.7%). For total biomass (Figure 1b), the relative RMSE ranged from high accuracy for SK5912 (6.9%) to very low accuracy for improved Deko (36.8%).

3.2. Model Validation: Performance with Farm-Level Grain Yield

The performance of the model in simulating grain yield was compared to the observed values under varying planting dates and cropping systems for each sorghum cultivar (Table 6). The planting dates across farms and cultivars were grouped under three months (referred to as "sowing month"), and the number of observations/farms revealed that 92% of farmers planted in the months of June and July, and only 8% of the farmers sowed in the month of August. For ICSV-400, the model under-predicted the mean observed yield for intercropping and mixed cropping systems, but the model over-predicted the mean observed yield for the sole cropping system across the sowing months. The lowest MBE of −977 kgha^{-1} was estimated in theJuly sowing month under the intercropping system, followed by the mixed cropping system, while the highest MBE (781 kgha^{-1}) was estimated under the sole cropping system in the month of June. The results showed that the model over-predicted the mean observed grain yield for Improved Deko across sowing months under the sole cropping system, with the lowest MBE (66 kgha^{-1}) estimated for the July sowing month, while the highest MBE (548 kgha^{-1}) was estimated for August sowing. The model over-predicted the grain yield across the sowing months and cropping systems except for the June sowing month under sole cropping system, for which lowest MBE of −234 kgha^{-1} was estimated. The highest MBE of 624 kgha^{-1} was estimated for July sowing under sole cropping. For CSR01, the model under-predicted the mean observed grain yield across sowing months and cropping systems except for the August sowing month under a mixed cropping system. Similarly, for SK5912, the model over-predicted the mean observed grain yield under the sole cropping system across sowing months, while the model under-predicted across sowing months for the mixed cropping system.

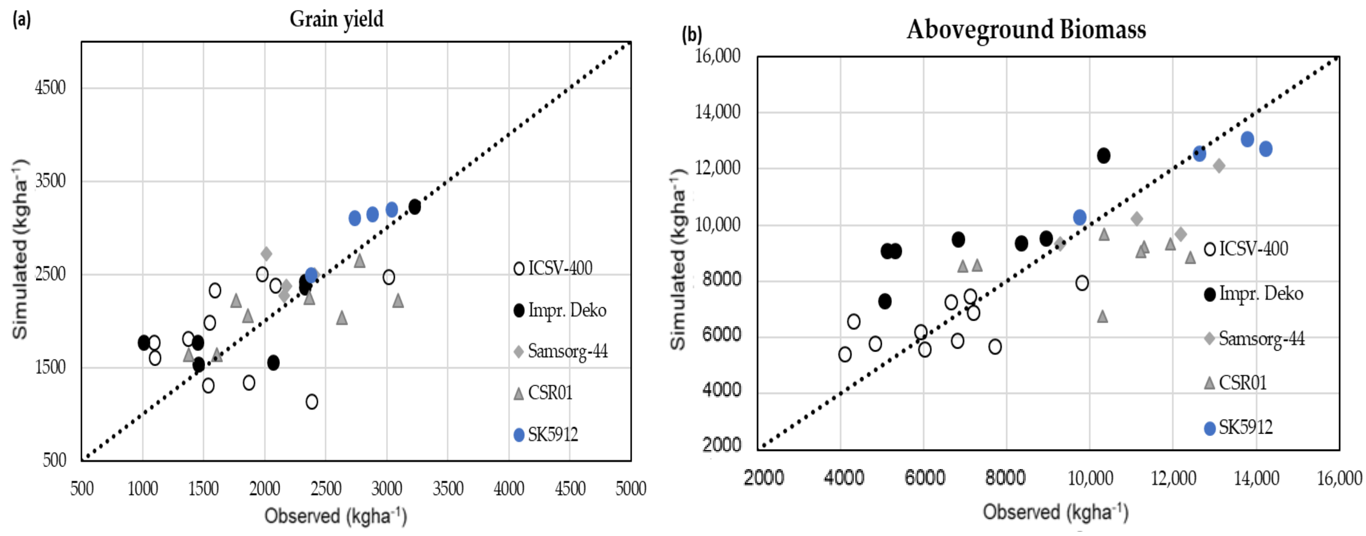

Figure 1. (**a**) Observed vs. simulated grain yield using experiment conducted in 2016–2018 growing seasons for cultivar ranges from early to late maturing. ICSV-400 (MBE = 103 kgha^{-1}; RMSE = 617 kgha^{-1}, RMSE$_n$ = 28.7%); Improved Deko (MBE = 114 kgha^{-1}, RMSE = 370 kgha^{-1}, RMSE$_n$ = 18.7%); Samsorg-44 (MBE = 279 kgha^{-1}; RMSE = 377 kgha^{-1}, RMSE$_n$ = 17.2%); CSR01 (MBE = −48 kgha^{-1}, RMSE = 301 kgha^{-1}, RMSE$_n$ = 13.8%); SK5912 (MBE = 234 kgha−1; RMSE = 254 kgha^{-1}, RMSE$_n$ = 9.2%). (**b**) Observed vs. simulated total biomass using experiment conducted in 2016–2018 growing seasons for cultivar ranges from early to late maturing. ICSV-400 (MBE = 28 kgha^{-1}, RMSE = 1249 kgha^{-1}, RMSE$_n$ = 19.5%); Improved Deko (MBE = 2344 kgha^{-1}, RMSE = 2621 kgha^{-1}, RMSE$_n$ = 36.8%); Samsorg-44 (MBE = −1100 kgha^{-1}; RMSE = 1432 kgha^{-1}, RMSE$_n$ = 12.5%); CSR01 (MBE = −976 kgha^{-1}, RMSE = 1687 kgha^{-1}, RMSEn = 16.5%); SK5912 (MBE = −429 kgha^{-1}; RMSE = 868 kgha^{-1}, RMSE$_n$ = 6.9%).

Table 6. Statistical indices for model validation of contrasted sorghum cultivars across planting date and cropping system from on-farm production technology between 2013 and 2017.

Sowing Month/Cultivar	Cropping System	N	Simulated	Observed	MBE	RMSE
ICSV400				kgha^{-1}		
June	Sole	535	2201	1420	781	1038
July	Intercropping	37	2007	2084	−77	700
	Mixed cropping	27	1698	2646	−948	1229
	Sole	461	2052	1488	564	942
Aug	Intercropping	13	1778	2754	−977	1029
	Mixed cropping	13	1850	2663	−814	959
	Sole	108	1897	1537	360	936
Improved Deko						
June	Sole	178	1656	1426	231	712
July	Sole	111	1554	1488	66	617
Aug	Sole	11	1492	943	548	598

Table 6. *Cont.*

Sowing Month/Cultivar	Cropping System	N	Simulated	Observed	MBE	RMSE
SamSorg-44						
June	Sole	22	1463	1697	−234	808
July	Sole	50	1586	962	624	915
	Intercropping	11	910	750	160	161
Aug	Sole	12	1623	1380	244	738
CSR01						
June	Intercropping	13	1573	2188	−615	624
	Mixed cropping	18	1524	1729	−206	640
	Sole	452	1335	1366	−31	726
July	Intercropping	23	1517	1700	−183	700
	Mixed cropping	13	1297	1973	−676	1203
	Sole	356	1566	1886	−320	952
Aug	Mixed cropping	15	1588	1388	200	258
	Sole	55	1474	1932	−458	940
SK5912						
June	Intercropping	26	1433	1305	128	873
	Mixed cropping	17	1157	1184	−26	834
	Sole	263	1437	1424	13	848
July	Intercropping	11	1147	1576	−429	873
	Mixed cropping	22	1169	2225	−1056	1285
	Sole	320	1587	1408	179	764
Aug	Intercropping	10	1323	1858	−535	824
	Mixed cropping	8	1135	1603	−744	809
	Sole	55	1786	1483	303	800

N—Number of observations/farms.

Figure 2 shows the model performance and the differences between the observed and simulated yield pooled together irrespective of the cropping systems and management practices for each cultivar. The mean observed grain yield for ICSV-400, CSR01, Improved Deko, Samsorg-44, and SK5912 are 1479, 1613, 1431, 1197, and 1446 kgha^{-1}, respectively. Further statistical indices showed that the grain yield of the ICSV-400, Improved Deko, and Samsorg-44 cultivars, respectively, were over-predicted against the mean observed grain yield; meanwhile, the yields of the CSR01, and SK5912 cultivars were slightly under-predicted compared to the mean observed yield. The results revealed low MBEs for CSR01 (−228 kgha^{1}), SK5912 (−241 kgha^{-1}), and Samsorg-44 (102 kgha^{-1}), respectively, with an RMSE of 642 kgha^{-1} estimated for improved Deko, and an RMSE of 655 kgha^{-1} estimated for Samsorg-44. The CV (%) described the level of variability for each cultivar simulated, which shows the lowest value of 8.9% for Samsorg-44, followed by Improved Deko (CV = 12.3%), while the highest variability was observed for CSR01 and SK5912 (CV = 25.5 and 18.4%).

3.3. Seasonal Rainfall and Temperature Trends across the Simulated Sites

The long-term (1985–2010) rainfall indicated that the rainy season starts in May and ends in October, with the highest peak observed in the month of August (Tables 7 and 8). The tables further revealed that about 50–60% of the seasonal rainfall was observed in the months of July and August, with a high inter-seasonal variability indicated by the coefficients of variation (CV), ranging from 18 to 23%. All of the study sites showed a distinct mono-modal rainfall pattern and warming temperature throughout the year. Figures 3 and 4 show the average monthly variations in the maximum and minimum temperatures across the selected sites in the Adamawa and Borno States. The maximum temperature uniformly decreases faster than the minimum temperature during the growing season (May–October). In addition, the estimated CV% values for the maximum temperature, ranging from 3.0 to 3.7%, are higher than those of minimum temperature, which range from 2.0 to 2.3% in both states, suggesting that no significant inter-annual variability was observed at the sites for either temperature.

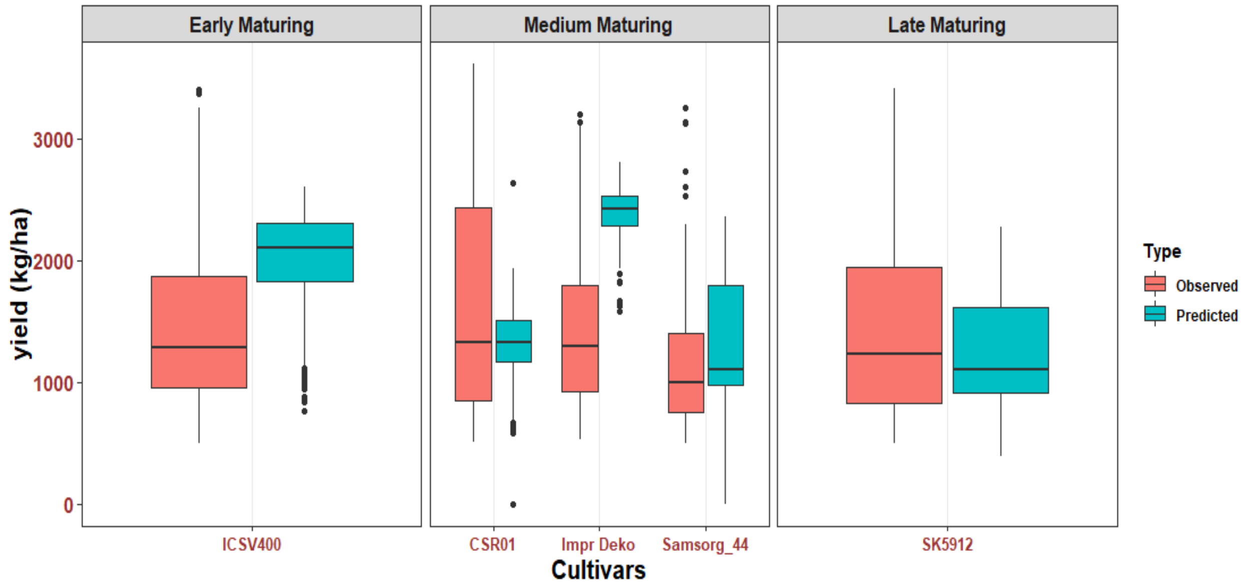

Figure 2. Yield (observed and simulated) using on-farm datasets from the 2013–2017 growing seasons from contrasting environments for five (5) sorghum cultivars ranged from early to late maturing. ICSV-400 (N = 1192; MBE = 535 $kgha^{-1}$; RMSE = 971 $kgha^{-1}$, CV = 13.8%); Improved Deko (N = 300; MBE = 960 $kgha^{-1}$, RMSE = 1169 $kgha^{-1}$, CV = 12.3%); Samsorg-44 (N = 100; MBE = 102 $kgha^{-1}$; RMSE = 655 $kgha^{-1}$, CV = 8.9%); CSR01 (N = 944; MBE = −228 $kgha^{-1}$, RMSE = 755 $kgha^{-1}$, CV = 25.5%); SK5912 (N = 731; MBE = −241 $kgha^{-1}$; RMSE = 879 $kgha^{-1}$, CV = 18.4%). Coefficient of variations (CV), N = number of observations.

Table 7. Analysis of mean monthly, seasonal rainfall (mm) and level of variability across the simulation sites in Adamawa State (1985–2010).

Site	May	Jun.	Jul.	Aug.	Sep.	Oct.	Seasonal	Stdev	C.V (%)
Demsa-Nassarawo	102.1	121.2	189.3	234.3	172.7	73.5	893	188	21
Mbula Kuli	95.9	115.7	186.5	225.8	168.1	58.6	851	181	21
Daneyel	99.8	118.1	202.9	240.5	156.9	54.4	873	191	22
Woroshi	103.3	126.4	216.5	244.0	156.4	55.7	902	191	21
Guyaku	117.9	155.9	228.9	308.8	176.6	99.1	1087	230	21
Tawa	134.2	149.6	237.1	293.3	192.4	97.2	1104	239	22
Lakumna	91.8	110.3	167.5	258.2	174.9	68.9	872	185	21
Chikila	98.5	106.5	178.4	249.7	165.2	67.8	866	186	21
Hushere Zum	120	133.8	211.7	266.5	196.7	113	1042	241	23
Dulmava	109.9	150.6	225.5	302.8	202.2	113.1	1104	247	22
Bare	91.9	107.4	176.9	244.2	162.9	80.6	864	194	22
Kodomti	91.1	109.5	176.8	243.2	170.2	75.0	866	194	22
Lakati-Libbo	95.2	109.6	186.8	250.2	155.2	74.9	872	191	22
Jonkolo-Lama	97.6	115.0	182.4	268.6	166.2	73.1	903	197	22
Sabon-Gari	99.8	119.5	211.3	269.7	181.8	82.1	964	212	22
Suktu	99.6	116.3	211.4	256.5	157.8	61.5	903	199	22
Yelwa-Jambore	102.1	125.4	206.6	218	163.5	52.2	868	189	22
Fufure	103.8	140.6	220.6	218.5	160.5	51.4	895	190	21

Seasonal—average total seasonal rainfall from May to Oct.; Stdev—Standard deviation from mean; CV—coefficient of variations (in percentage).

Table 8. Analysis of mean monthly, seasonal rainfall (mm) and level of variability across the simulation sites in Borno State from 1985 to 2010.

Site	May	Jun.	Jul.	Aug.	Sep.	Oct.	Seasonal	Stdev	C.V (%)
Balbaya	87.9	141.3	202.9	287.9	167.4	67.4	955	206	22
Briyel	93.2	129.0	174.2	242.7	182.7	61.1	883	182	21
Jara-Dali	78.4	136.8	202.8	289.0	204.4	80.3	992	217	21
Kabura	72.5	142.4	209.7	316.1	149.3	48.4	939	188	20
Mathau	78.3	144.4	204.4	312.1	165.6	51.9	957	174	18
Tum	86.2	149.8	218.1	317.4	170.0	56.9	998	204	20
Buratai	77.4	144.3	210.9	318.4	148.5	45.6	945	191	20
Kwajaffa	99.7	142.3	204.3	306.7	179.3	51.2	983	186	19
Puba Vidau	96.6	144.2	199.6	299.8	188.3	60.3	989	191	19
Sakwa Hema	93.3	144.2	206.9	307.4	176.8	60.2	989	186	19
Bila-Gusi	98.9	124.5	190.6	268.6	183.4	75.7	942	189	20
Kurba Gayi	85.5	145.9	213.1	303.1	166.2	61.1	975	199	20
Gwaskara	83.5	142.1	198.5	295.4	201.6	74.9	996	192	19
Kubo	97.3	121.6	181.9	262.2	192.2	72.3	927	186	20
Lakundum	85.2	146.0	220.2	307.1	158.2	77.9	995	213	20

Seasonal—average total seasonal rainfall from May to Oct.; Stdev—Standard deviation from mean; CV—coefficient of variations (in percentage).

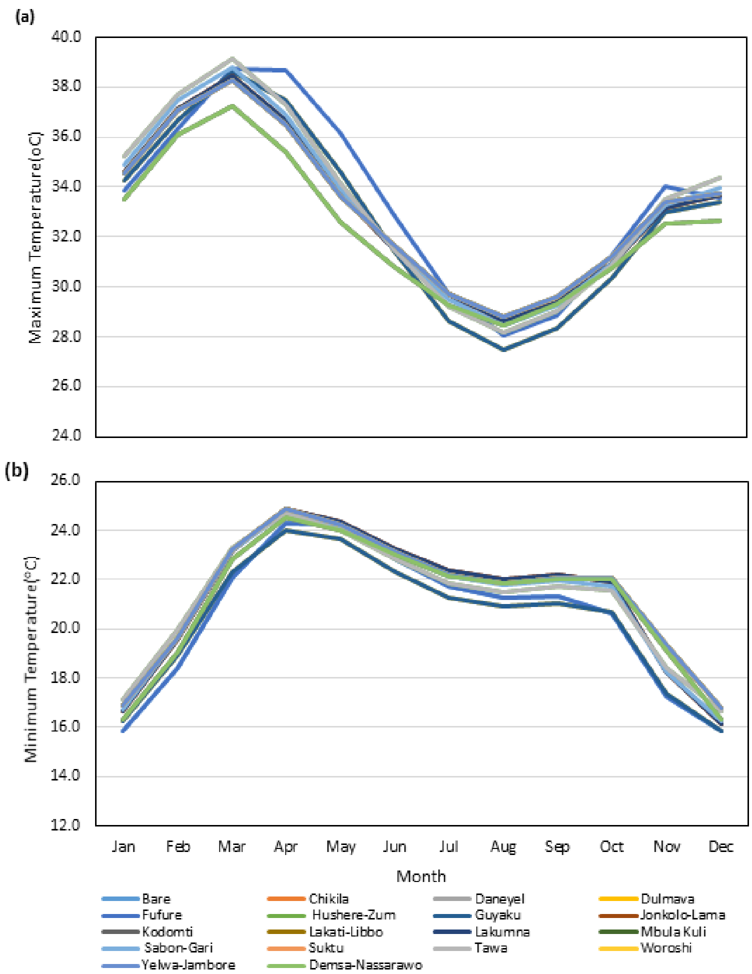

Figure 3. Average monthly variation of (**a**) maximum temperatures and (**b**) minimum temperatures between 1985 and 2010 across the simulation sites in Adamawa State. The coefficients of variation (CV) ranged from 3.0 to 3.7% for maximum temperature and 2.0 to 2.3% for minimum temperature.

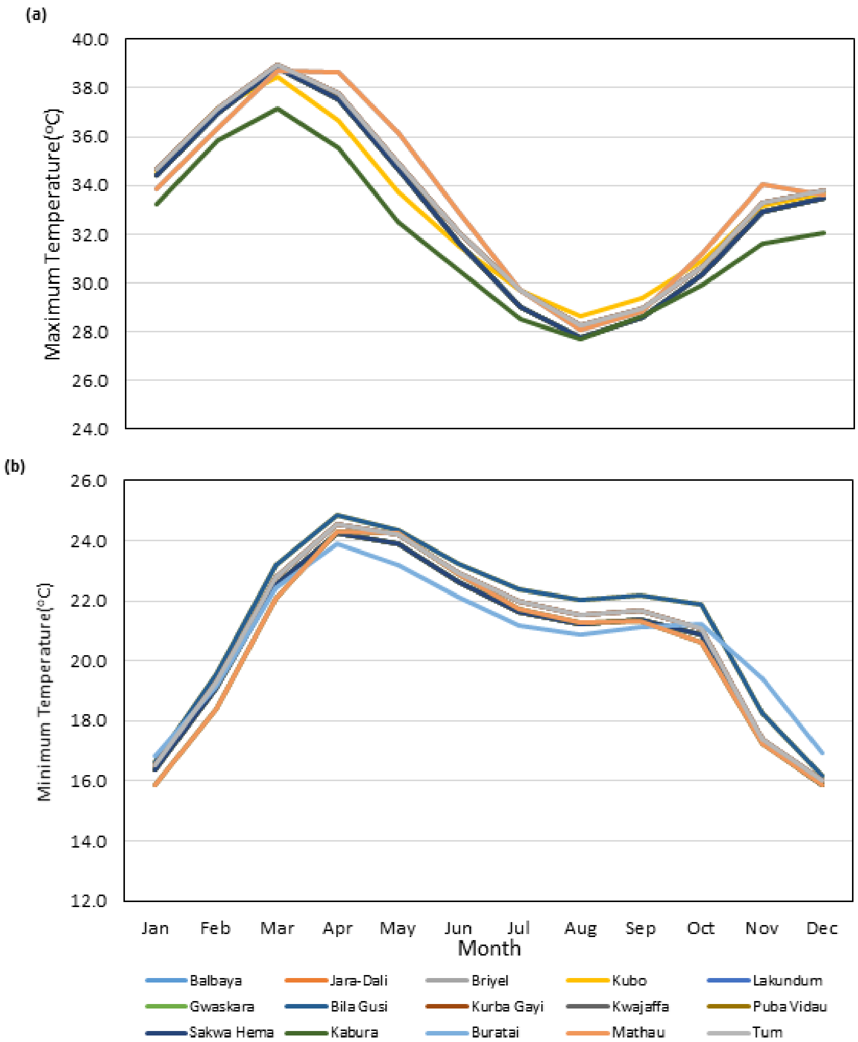

Figure 4. Average monthly variations of (**a**) maximum temperatures and (**b**) minimum temperatures between 1985 and 2010 across the simulation sites in Borno State. The coefficients of variation (CV) ranged from 3.0 to 3.7% for maximum temperature and 2.0 to 2.3% for minimum temperature.

In Adamawa State (Table 7), the seasonal rainfall (May-Oct.) for all of the sites over the 31-year period (1985–2010) ranged from 851 to 1104 mm. It was observed that the rainfall in Dulmava, Hushere Zum, and Guyaku and Tawa was slightly higher (>1000 mm) than in the other locations. The average monthly maximum temperature across the sites over the climatic period ranged from 27.5 to 39.1 °C (Figure 3a), while the average monthly minimum temperature ranged from 15.8 to 24.9 °C (Figure 3b). In Borno State (Table 8), the seasonal rainfall over the 31-year period (1985–2010) across the sites ranged from 883–998 mm with high inter-seasonal variability, varying from 18 to 22%. The average monthly maximum temperature across the sites over the climatic period ranged from 27.8 to 38.9 °C (Figure 4a), while the average monthly minimum temperature ranged from 15.5 to 24.7 °C (Figure 4b).

3.4. Seasonal Analysis of Planting Windows and Sorghum Cultivars on Simulated Grain Yield and Water Use Efficiency (WUE_{grain})

Table 9 shows the mean simulated grain yield (GY) and the water use efficiency for grain yield (WUE_{grain}) of the sorghum cultivars across four different planting windows (PW1, PW2, PW3, and PW4) in the three agro-ecological zones (AEZs) between 1985 and 2010. The mean simulated grain yield and WUE_{grain} showed a decrease with delayed planting (PW1 to PW4) for all five sorghum cultivars. Following the sowing rule strategies implemented for the simulation, the model outputs indicate approximately 45 days of PW, from 25 May to 10 July across AEZs, for all sorghum cultivars except for SK5912, which has approximately 35 days of planting window varying from 25 May and 30 June in the NGS and SGS. A higher mean GY and WUE_{grain} were simulated in the NGS than in the SS and SGS zones. Additionally, the early and medium-maturing sorghum cultivars (ICSV400, Improved Deko, CSR01, and Samsorg44) had higher simulated GY and WUE_{grain} values than those of the late-maturing cultivar (SK5912).

Table 9. Mean simulated grain yield and Water Use Efficiency for grain yield (WUE_{grain}) of sorghum cultivars across different planting windows (PWs) and agro ecological zones.

PW/C	NO	Grain Yield					WUE_{grain}				
		ICSV400	Impr. Deko	CSR01	Samsorg-44	SK5912	ICSV400	Impr. Deko	CSR01	Samsorg-44	SK5912
Sudan Savanna (SS)		kgha^{-1}					kgha^{-1} mm^{-1}				
PW1	420	2321	2211	2340	2097	1703	7.3	6.6	5.0	4.6	3.2
PW2	420	2309	2170	2205	1981	1580	7.3	6.4	4.6	4.2	3.0
PW3	420	2255	2148	1895	1760	1252	6.9	6.2	4.0	3.7	2.4
PW4	420	2228	2145	1778	1613	1128	6.8	6.2	3.8	3.5	2.3
Mean		**2278**	**2168**	**2054**	**1863**	**1416**	**7.1**	**6.3**	**4.4**	**4.0**	**2.7**
Northern Guinea Savanna(NGS)											
PW1	480	2323	2234	2750	2536	2358	7.7	7.0	6.6	6.1	5.0
PW2	480	2315	2188	2677	2447	2128	7.8	6.8	6.0	5.5	4.2
PW3	480	2236	2171	2657	2386	1856	7.2	6.3	5.8	5.3	3.7
PW4	480	2223	2138	2644	2375	1654	7.1	6.5	6.0	5.4	3.5
Mean		**2274**	**2182**	**2682**	**2436**	**1999**	**7.5**	**6.7**	**6.1**	**5.6**	**4.1**
Southern Guinea Savanna(SGS)											
PW1	90	1959	1865	2192	1967	1733	6.7	6.0	5.5	5.1	3.9
PW2	90	1939	1815	2091	1878	1655	6.7	5.9	5.1	4.7	3.6
PW3	90	1920	1841	2106	1898	1488	6.4	5.8	5.1	4.7	3.3
PW4	90	1903	1814	2059	1850	1530	6.4	5.8	4.9	4.5	3.3
Mean	**90**	**1930**	**1834**	**2112**	**1898**	**1602**	**6.6**	**5.9**	**5.2**	**4.7**	**3.5**

Impr.—improved; PW—planting windows [16–31 May (PW1), 1–15 Jun (PW2), 16–30 Jun (PW3), 1–15 Jul (PW4)]; C—Cultivar; NO—Number of observations.

For the SS zone, the optimal sowing window simulated ranged from 25 May to 30 June (PW 1 to PW3) for CSR01 and Samsorg-44 and from 25 May to 15 June (PW1 and PW2) for SK5912, while, for the ICSV400 and Improved Deko cultivars, sowing can extend to 10 July. In the NGS and SGS zones, the optimal planting window ranged from 25 May to 10 July for all sorghum cultivars except for SK5912, for which 25 May to 30 June was simulated to be the optimal planting window. The highest mean WUE_{grain} of 6.4–7.8 kgha^{-1} mm^{-1} was simulated for ICSV400. Next to it was improved Deko with a WUE_{grain} of 5.8–6.8 kgha^{-1} mm^{-1}, and SK5912 was simulated to have the lowest WUE_{grain} (2.3–4.2 kgha^{-1} mm^{-1}) across the three AEZs

Table 10 shows the mean simulated grain yield for evaluating the adapted sorghum cultivars across sites based on an increased yield threshold of ≥1500 kgha^{-1} and against the national average grain yield of 1160 kgha^{-1}. In the SS zone, the simulated mean grain yield across the selected sites ranged from 2023 to 2673 kgha^{-1} for ICSV400, 1886–2509 kgha^{-1} for Improved Deko, 1022–3707 kgha^{-1} for CSR01, 939–3324 kgha^{-1} for Samsorg-44, and 730–2847 kgha^{-1} for SK5912, respectively. The CV shows the variability of the simulated

GY across sites, with lower values estimated by ICSV400 (10%) and Improved Deko (9%) compared to higher values estimated by CSR01 (46%), Samsorg-44 (44%), and SK5912 (56%).

Table 10. Mean simulated grain yield (kgha^{-1}) for evaluating adapted sorghum cultivars across sites and AEZs based on increased yield threshold.

AEZ	N-Site	ICSV400	Impr. Deko	CSR01	Samsorg-44	SK5912
Sudan Savanna (SS)	Balbaya	2236	2132	1467	1368	1106
	Briyel	2208	2118	1983	1784	1450
	Buratai	2290	2130	2555	2426	1926
	Dulmava	2363	2301	2249	2001	1439
	Guyaku	2172	2069	1371	1296	1110
	Jara-Dali	2092	2052	1708	1545	1242
	Kabura	2636	2480	3707	3324	2847
	Kurbo Gayi	2673	2509	3645	3247	2445
	Kwajaffa	2328	2221	1624	1448	919
	Lakundum	2276	2151	2612	2289	1621
	Mathau	2013	1886	1067	1029	730
	Puba Vidau	2157	2026	1022	939	783
	Sakwa Hema	2292	2180	1902	1723	1112
	Tum	2157	2098	1847	1653	1096
	Mean	**2278**	**2168**	**2054**	**1863**	**1420**
	CV(%)	**10**	**9**	**46**	**44**	**56**
Northern Guinea Savanna (NGS)	Bare	1926	1803	1269	1174	940
	Bila Gusi	2126	2044	2325	2054	1580
	Chikila	2402	2331	3152	2914	2201
	Daneyel	2028	1945	1807	1615	1247
	Gwaskara	2498	2372	2957	2592	1789
	Hushere Zum	2180	2079	1777	1599	1213
	Jonkolo—Lama	2208	2141	2657	2564	2149
	Kikan_Kodomti	2060	1992	2301	2024	1557
	Kubo	2406	2336	3761	3432	3140
	Lakati-Libbo	2123	2057	1954	1743	1411
	Lakumna	2414	2344	3199	3298	2790
	Mbula Kuli	2237	2176	2685	2366	2120
	Sabon Gari	2495	2360	3387	2999	2680
	Suktu	2314	2221	2874	2538	2052
	Tawa	2458	2328	3127	2753	2294
	Wuroshi	2512	2390	3676	3310	2824
	Mean	**2274**	**2182**	**2682**	**2436**	**1999**
	CV(%)	**11**	**11**	**30**	**30**	**41**
Southern Guinea Savanna (SGS)	Fufure	1306	1165	1010	971	891
	Nassarawo Demsa	2330	2220	3049	2707	2325
	Yelwa-Jambore	2154	2117	2276	2017	1589
	Mean	**1930**	**1834**	**2112**	**1898**	**1602**
	CV(%)	**24**	**27**	**42**	**40**	**43**

Impr.—improved; CV(%)—Coefficients of variations in the percentage.

In NGS zone, the simulated mean grain yield across the sites ranged from 1926 to 2512 kgha^{-1} for ICSV400, 1841–2390 kgha^{-1} for Improved Deko, 1269–3761 kgha^{-1} for CSR01), 1174–3432 kgha^{-1} for Samsorg-44, and 940–3140 kgha^{-1} for SK5912. The variability of the GY across sites indicated low CV% for ICSV400 and Improved Deko (11%) compared to high CV% estimates for CSR01 (30%), Samsorg-44 (30%), and SK5912 (41%). In the SGS zone, the simulated mean grain yield across the sites ranged from 1306 to 2330 kgha^{-1} for ICSV400, 1165–2220 kgha^{-1} for Improved Deko, 1010–3049 kgha^{-1} for CSR01, 971–2707 kgha^{-1} for Samsorg-44, and 891–2325 kgha^{-1} for SK5912. The CV% was generally high for all cultivars, ranging from 24 to 43%. At the mean grain yield threshold of ≥1500 $kgha^{-1}$, all cultivars simulated were found to be adapted for cultivation except at the Fufure site.

4. Discussion

This study contributes to efforts to develop climate risk strategies for the sorghum-based mixed farming systems in northern Nigeria. The evaluation of the model calibration and its validation with an independent dataset (farm-level yield) under different management, soils, and climatic conditions allow the APSIM-sorghum model to be applied to understanding the dynamics of this heterogeneous farming system. The application of crop modelling to develop adaptation strategies to changing climatic conditions was earlier demonstrated for sorghum by [22,31] and for maize by [65]. The predicted LAI-max and total leaf number (TLN) indicated a low accuracy (RMSE varied from 20 to 30%) due to the relatively higher values simulated for July sowing dates resulting in a higher mean grain yield simulated under calibration. However, the difficulty in predicting TLN could be linked to the fixed thermal time targets for each of the phases before flowering in the APSIM-sorghum module. These thermal time targets are not directly linked to leaf initiation and appearance [66]. The predictions of the grain yield (GY) and total biomass (TB) ranged from high accuracy $RMSE_n$ (SK5912: 9.2% for GY; 6.9% for TB) to very low accuracy $RMSE_n$ (ICSV400: 28.7% for GY; Improved Deko: 36.8% for TB) when evaluated against the observed mean. The low accuracy for GY and TB could be associated with the simulation of leaf initiation and leaf appearance, which are important for the accurate prediction of morphological traits [31,67].

The use of model evaluation using simple on-station trial datasets is the common procedure for developing new cultivar parameterizations. However, evaluating models with multi-locational, on-farm trial datasets has proven difficult, with many uncertainties, especially across the different soil, climate, and cropping systems considered [66]. The study presented here utilized comprehensive data from on-farm trials using different planting dates, cropping systems, fertilization strategies, soil types, and management regimes representing the heterogeneous farming system of northern Nigeria. The performance of the model was satisfactory under varying planting dates (referred to as "sowing month"), cropping systems, and sorghum cultivars as described in Table 6. With exception of the CSR01 and SK5912 cultivars, the model's predictions had a lower MBE, either positive or negative, for the sole cropping system in the July sowing month compared to the June and August sowing months. These results could be explained by the pattern of rainfall that serves as a means of crop water utilization, which in turn determines the biomass accumulation for the grain yield. The high rainfall variability across the study sites suggests the importance of matching crop duration to the length of the growing period in the region because sorghum is a short-day crop and most West African cultivars are photoperiod sensitive that could only be produced under rainfed conditions [23,31]. These conditions place limits on the use of long-season sorghum cultivars in some locations even within the same AEZ, which permits the choice of early-medium maturing cultivars. Although the soil fertility composition across the sites suggested low values for organic carbon (OC) and nitrogen N, the pH values indicated ideal soils (neutral to alkaline conditions) suitable for plant growth of sorghum [51].

Our simulations revealed that the optimal PWs and suitable sorghum cultivars were influenced by the dates of sowing, soil types, rainfall amount, and pattern across sites and AEZs. In addition, this has to do with the cultivar's sensitivity or insensitivity to photoperiod and inherently early/late flowering traits [68]. These results corroborate the findings by [23], who reported that inherent soil fertility and rainfall patterns can greatly influence the yield when sowing is delayed. Both early and medium-maturing sorghum cultivars (ICSV400, Improved Deko, CSR01, and Samsorg-44) produced higher GY and WUE_{grain} than those of the late-maturing cultivar (SK5912) at varying PWs and were found suitable to most sites across the AEZs. The optimal PWs slightly varied among the cultivars and AEZs. Our simulation results suggest an optimal sowing window for the ICSV400 and Improved Deko cultivars from 25 May to 10 July (45 days) and an optimal window for CSR01 and Samsorg-44 from 25 May to 30 June (35 days) in the SS zone. The results further revealed that the planting of CSR01, Samsorg-44, and SK5912 beyond these dates will significantly reduce the mean grain yield by 7%, 9%, and 11%, with no significant yield change estimated for the ICSV400 and Improved Deko cultivars. In the NGS and SGS zones, the optimal PWs ranged from 25 May to 10 July (45 days), except for SK5912, for which 25 May to 30 June (35 days) was simulated.

These results showed the use of early and medium maturing sorghum cultivars with higher yield and the most suitable cultivars to varying soil types simulated across the AEZs. In the SS zone, the level of variability suggests that ICSV400 and Improved Deko were highly suitable for cultivation across the sites; CSR01 and Samsorg-44 were suitable for cultivation in almost all the sites with exception of Guyaku, Balbaya, Mathau Puba Vidau, and Kwajaffa, while the late maturing cultivar (SK5912) adapted for cultivation only in 4 (Buratai, Kabura, Kurbo-Gayi, Lakundum) out of 14 sites. These results suggest only 4 out of the 5 sorghum cultivars may be suitable for cultivation under the current climatic conditions. In NGS, at a mean grain yield threshold of $\geq$1500 kgha^{-1} and the level of variability across the sites, all the cultivars were found to be adapted and suitable for cultivation in most sites, except for CSR01 and Samsorg-44 at Bare, and SK5912 at Bare, Daneyel, Hushere Zum, and Lakati-Libbo, respectively. The simulated yields of all the sorghum cultivars at the Fufure site in the SGS zone were found to be below the yield threshold of $\geq$1500 kgha^{-1}, and these results could be associated with sandy soil in the area and the very low soil fertility resulting in low water retention for crop growth. Also, a late PW reduced the grain yield due to early terminal drought towards the cessation of the growing period, resulting in a high temperature that affects the grain filling period, i.e., slows the rate of grain filling and accelerates senescence, thereby decreasing the photosynthetic activities per unit leaf area [69]. In addition, the increased temperature and water deficit experienced in the late planting window, particularly in PW4, can reduce the crop canopy (leaves and tillers) and decrease the biomass production, which in turn reduces the grain yield.

5. Conclusions

The validation of the model with farm-level grain yield enhanced the predictive capacity of the model for simulating diverse climatically driven yields under different fertilization strategies, sowing dates, and planting densities for the contrasting sorghum cultivars. However, our model application used different PWs based on climate-smart management practices that include the recommended fertilizer application rate and optimal hill population against the farmer practices for sorghum production in Northern Nigeria, geared towards disseminating and increasing the adoption of climate-smart technology, which is the basis for higher productivity. The optimum PWs were simulated as being between 25 May and 30 June for CSR01 and Samsorg-44 but were extended to 10 July for ICSV400 and Improved Deko, while low yield was simulated for SK5912 for all planting windows in the SS zone. In the NGS and SGS zones, the optimal PWs ranged from 25 May to 10 July (45 days) for all cultivars except for SK5912, for which predicted optimal PWs ranged from 25 May to 30 June (35 days). The mean simulated GY for SK5912 fell below the threshold of $\geq$1500 kgha^{-1} in Bare, Daneyel, Hushere Zum, and Lakati-Libbo'. In addition, at the Fufure site in SGS, all of the sorghum cultivars were simulated to be below the yield threshold $\geq$1500 kg ha^{-1} due to sandy soil texture found in the area, with the very low soil fertility resulting in a low water retention capacity for growth. Under climate change, the adoption of appropriate climate-smart technology sorghum will improve food security and reduce greenhouse gas emissions. It may therefore be concluded that the predicted optimal PWs for sorghum would substantially assist the smallholder farmers and seed producers in the region in their choice of cultivars to promote for high yields relative to growing sites and agro-ecologies.

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